DECISION SUPPORT MODEL TO COMPARE HAZARDOUS WASTE SITE REMEDIATION PROCESS ALTERNATIVES

THESIS

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THESIS

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Preface

The purpose of this study was to develop a decision support model to aid the United States Air Force in identifying if and when alternative methods of remediating hazardous waste sites are preferred to the traditional methods. An additional objective of this research was to model the decision making process of the Remedial Project Manager with a combination of an influence diagram and decision tree.

Even though this study was directed towards alternative methods of remediating hazardous waste sites on the National Priority List, the decision support model is not limited to use at NPL sites. The model could be used to quantify the uncertainties and benefits of alternative methods at all Installation Restoration Program sites.

This research effort would not have been possible without the contribution and support of many individuals. I would like to express special thanks to Dr. Thomas Hauser and Colonel Gregory Parnell, whose knowledge, experience, and willing assistance, made this an outstanding learning experience. I would also like to thank Mr. Vern Cromwell who suggested the topic and Mr. Dean Campbell for his computer assistance. I would like to give special thanks to my wife, Kami, for her love, understanding, and support throughout the thesis effort and master degree program and my daughter, Maggie, for her patience and the inspiration she provided to me. Lastly, I would like to thank my family and friends for their encouragement in making this work possible.

Christopher E. Findall

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Abstract

This research focuses on the development of a decision support model to identify the preferred methods of site characterization and treatment technology identification using the principles of decision analysis theory. The model provides an effective decision making tool to evaluate and compare the feasibility of using alternative methods of completing the RI/FS process.

Given a specific site remediation project, the users of this model can enter site-specific cost, duration and likelihood values to determine the expected value for various alternative processes. This thesis postulates that the alternative having the highest expected value is considered the "preferred" alternative. In calculating the expected value of an alternative, the cost and duration for each alternative and outcome of uncertain events are evaluated.

This research also includes a representative case study to illustrate the use of the decision support model. Although the case study addresses a hypothetical case, the model can be applied to any hazardous waste remediation project.

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I. Introduction

Background

The cleanup of hazardous waste has become a major problem facing our nation today. Public interest concerning the health threats posed by hazardous waste began in the mid 1970s and are exemplified by the environmental disasters that occurred at Love Canal, New York and Times Beach, Missouri. As a result of the public concerns generated by these and other incidents, the United States Congress passed the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) in 1980.

CERCLA, also known as Superfund, gives the United States Environmental Protection Agency (USEPA) the authority and resources required to cleanup abandoned or inactive hazardous waste sites and respond to emergencies related to these waste sites. A key component of CERCLA is 40 CFR Part 300: National Oil and Hazardous Substances Pollution Contingency Plan, also known as the National Contingency Plan (NCP), which provides specific direction concerning the remedial action process followed by the USEPA and private parties for conducting the cleanup of hazardous waste sites (Lee, 1993:274).

The NCP divides the remedial action process into three stages: planning/investigation, execution, and close-out (USAF, 1992:1-3). The cleanup of hazardous waste sites in the Air Force is performed through the Installation Restoration Program (IRP). The Air Force's IRP remedial action process mirrors the process outlined in the NCP (USAF, 1992:3-1).

The Superfund process has been widely criticized for being extremely slow and costly to complete clean up actions. Critics claim the process creates lengthy cleanups and increases the cost. The average cost of a Superfund cleanup in 1993 was $25 million and the average project duration was 10 years (Ember, 1993b:19 and Elliot, 1992:12). The process is progressing so slowly, that as of 1992, the Air Force had not removed any of its 32 sites from the National Priority List (DoD, 1992: A-3 to A-5).

As a result, use of the Observational Method to characterize sites and the presumptive remedy approach to identify and select treatment technologies have been proposed to streamline the process of cleaning-up hazardous waste sites, thus reducing total project cost and duration. Proponents of the Observational Method claim proper application of the process will reduce both cleanup time and costs; but, a major shortcoming of the Observational Method is that it attempts to design the remediation strategy before fully characterizing the site (Brown, 1990:479). Therefore, this strategy creates a potentially greater risk of implementing a remediation design that will ultimately fail to meets cleanup standards, thereby possibly incurring major clean-up costs without affecting an acceptable remediation.

Proponents of the presumptive remedy approach argue that lengthy and costly feasibility studies are not required at sites that are similar to previous hazardous waste clean-up sites (USEPA, 1992a:10). They reason that the best treatment technology used successfully at one site will be the best treatment technology for any similar site (USEPA, 1992a:10). Therefore, this strategy creates a potentially greater risk of selecting a treatment technology that is not effective for the specific remediation site, thereby possibly incurring additional investigation time and costs.

Goals

Recognizing the current CERCLA process is very costly and lengthy, the USAF has a vested interest in implementing improvements in the remediation process. Currently, the Air Force is unsure of either adopting or rejecting the alternative processes. Mr. Scott Edwards, HQ USAF/CEV reports the Air Force policy is still uncommitted in regards to the use of the Observational Method (Edwards, 1994). Despite the lack of a clear policy, some Air Force project managers have applied the Observational Method at a few IRP sites (Cromwell, 1994).

Before the Air Force finalizes an alternative clean-up policy, it is obvious that a decision tool is needed to evaluate and compare the possible alternatives with the current process to avoid either incorrectly adopting a new process or failing to adopt a better alternative. By applying the principles of decision analysis, it is the goal of this study to create a decision support model to aid the Air Force in establishing a definitive policy and/or aid project managers in deciding which approach is best for a given hazardous waste site clean-up scenario.

Specific Objectives

The research objectives of this study therefore are:

1. Identify significant alternative remediation processes.

2. Develop an influence diagram and decision tree to model the problem structure, uncertainty, and preferences of the remediation process.

3. Using the decision support model, evaluate and compare the traditional and alternative processes.

4. Identify if and when alternative remediation processes are preferred to the traditional process.

II. Literature Review

What Is Superfund?

In 1980, Congress passed the Comprehensive Environmental Restoration, Compensation, and Liability Act (CERCLA), also known as Superfund, to reduce the risk to human health and the environment from hazardous waste (Lee, 1993:273). CERCLA specifically addresses the identification, characterization, and cleanup of releases into the environment (Rudolph, 1993:1-2). The National Contingency Plan (NCP) specifically details the procedures which must be followed in conducting CERCLA response actions (Lee, 1993:274).

Under CERCLA and the NCP, there are two types of response actions: removal actions and remedial actions (Lee, 1993:275). Each type of response action has a unique specific process (Lee, 1993:275). Removal actions are intended to diminish the immediate threat of a hazardous waste site, while remedial actions are long-term, permanent cleanups (Lee, 1993:275). For example, consider a case in which a hazardous waste site is discovered that contains leaking, buried drums. The USEPA immediately removes the remaining drums and liquid waste and later the USEPA incinerates the contaminated soil and installs a pump and treat system to clean up the ground water. Immediately uncovering and disposing of the drums is a *removal action* because it decreased the immediate danger but did not completely restore the site. On the other hand, incinerating the soil and installing the pump and treat system are *remedial actions* because they are intended to restore the site to original conditions.

Hazardous waste sites that pose the most significant risk to human health and the environment are placed on the National Priority List (NPL). Both CERCLA and the NCP mandate the USEPA score and rank potential hazardous waste sites based on the risk to public health (Lee, 1993:273). Those sites that score above the minimum threshold are required to be placed on the NPL (Lee, 1993:273). Placement on the NPL is significant since sites on the NPL must comply with the more stringent process for remedial actions set forth in CERCLA and the NCP (Lee, 1993:277).

The remedial process, as required by CERCLA and the NCP, is divided into three stages with individual steps within each stage, as shown in Figure 2-1 (USAF, 1992:1-3). The first stage, Planning and Investigation, is comprised of the Discovery & Notification (D&N), Preliminary Assessment (PA), Site Investigation (SI), and Remedial Investigation/Feasibility Study (RI/FS) steps (Rudolph, 1-3). D&N is the discovery of an actual or suspected release to the environment (Rudolph, 1993:1-3). After a potential site is identified, the PA reviews existing site information to determine if further study is required (Rudolph, 1993:1-4). If the PA warrants further investigation, a SI is conducted to observe and sample the site in order to confirm a possible release of contaminants to the environment and assess the nature of the threats (Rudolph, 1993:1-5). After the SI is completed, the RI is conducted to more fully determine and characterize the nature and extent of the problem. The FS develops and evaluates treatment technologies for remedial action (Rudolph, 1993:6-2). The first three steps are sequential while the RI and FS (RI/FS) are usually conducted simultaneously (Rudolph, 1993:1-6).

Between the Planning/Investigation and Cleanup Stages, the remedy is selected (Rudolph, 1993:1-7). The Record of Decision (ROD) documents the final remedy decision (Rudolph, 1993:1-7). The final remedy is selected based on nine separate criteria established by the USEPA (Rudolph, 1993:1-7).

Once the final remedy is selected, the Cleanup or Execution Stage begins. The Cleanup stage consists of two steps, the Remedial Design (RD) and the Remedial Action (RA) (USAF, 1992:1-6). The RD is the actual engineering design of the selected remedy while the RA is the construction and implementation of the of the RD (USAF, 1992:1-6).

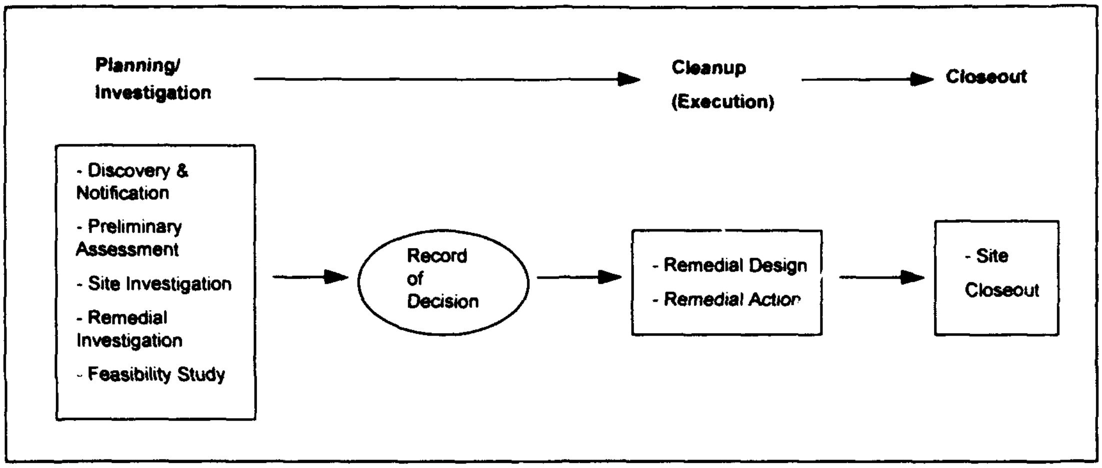

Figure 2-1. CERCLA and IRP Response Action Process Stages and Steps (USAF, 1992:1-3).

After completing the RA, the Close-out Stage begins. The Close-out Stage is the process required to document and confirm the site is no longer considered a threat to human health and the environment (USAF, 1992:1-7). At the end of the Close-out Stage, the site is removed from the NPL.

What Is the Installation Restoration Program?

The Installation Restoration Program (IRP) is the Department of Defense's (DoD) management program to implement the requirements of CERCLA. Section 120 of CERCLA requires federal facilities to comply with the Act to the same extent as non-Federal facilities (Rudolph, 1993:1-1). The objective of the IRP is to identify, investigate, clean up, and close out IRP sites (USAF, 1992:1-1). By law, the remedial action process must be performed consistent with

CERCLA, therefore, the IRP process is the same as outlined in Figure 2-1.

What Is Wrong With Superfund and the IRP?

Critics point to numerous problems with Superfund, but most of the criticism is directed at the slow progress and high cost associated with hazardous waste site cleanups. The criticism has been directed at the USEPA for their handling of Superfund sites and at the DoD for its handling of IRP sites. Congress has established panels to specifically look into environmental restoration at DoD facilities (House Committee, 1988:3). At a hearing of the Environmental Restoration Panel for the House Committee on Armed Services, the chairman of the panel emphasized Congress' concern over the time required to complete the full CERCLA cleanup process at DoD facilities (House Committee, 1988:6).

One of the chief concerns of CERCLA critics is the enormous costs associated with Superfund cleanups. In 1987, former USEPA administrator William Ruckelshaus established the Coalition on Superfund comprised of representatives from 18 private companies to conduct independent research on Superfund reform (Ember, 1993a:30). The coalition reported the average cost of Superfund cleanups had tripled from USEPA estimates of $7 million per site in 1981 to an average cost of $25 million in 1993 (Ember, 1993a:30). A 1991 study by the University of Tennessee estimates the cost of cleanups under Superfund and the Resource Conservation and Recovery Act (RCRA) could reach $750 billion over the next 30 years under current policies (Russell, 1991:iv).

The DoD and Air Force are experiencing the same enormous costs for the IRP. According to Sherri Wasserman Goodman, Undersecretary of Defense for Environmental Security, the DoD has spent $6.5 billion during fiscal years 84-93 ("Environmental Restoration Effort...", 1993:16). As of FY 91, the Air Force had spent $679 million for cleanup at 32 NPL sites. Of the $679 million, $429 million had been spent just conducting the RI/FS steps (Appendix A).

Despite the enormous amount of money spent on cleanups, progress at NPL sites is slow. The USEPA reported that as of June 1992, 1325 sites had been placed on the NPL since 1980 and only 40 sites have been deleted from the NPL (USEPA, 1992b:9) The average time to clean up a site is currently 10 years (Elliot, 1992:12). Of these 10 years, seven years is typically spent studying and assessing the site (Elliot, 1992:12).

Data collected from the Defense Environmental Restoration Program annual report to Congress for Fiscal year 1991 (See Appendix A) shows clean up progress at Air Force facilities is suffering from the same slow process (DoD, 1992: A-3 to A-5). Of the 32 installations on the NPL, none have completed cleanup and only two have completed the RI/FS stage as of the end of FY91. The 30 remaining installations were in the RI/FS stage and had been for an average of over four years.

Critics claim the process itself creates lengthy cleanups and increases the cost. Duplancic and Buckle claim the current process forces engineers at hazardous waste sites to choose the safest course rather then the most cost-effective or technically appropriate (Duplancic and Buckle, 1989:68). The traditional approach to site characterization focuses on developing a complete picture in terms of data collection (Brill, 1994:51). As a result, the tendency currently is to investigate waste sites almost endlessly in an effort to eliminate uncertainty (Duplancic and Buckle, 1989:69). As more data is collected and analyzed, the site investigation cost and duration increase. Also, dividing the process into individual phases causes longer site investigations thus lengthening the cleanup process (Duplancic and Buckle, 1993:52).

What Are the Alternatives?

In response to the slow progress and high cost, both the USEPA and industry have proposed one alternative approach to streamline the site characterization process and another alternative approach to streamline the feasibility study and technology assessment process. The first alternative approach, the Observational Method, is an application of the Observational Method developed by Carl Terzaghi in the field of geotechnical engineering (Einstein, 1991:1773). The Department of Energy, in coordination with the USEPA, has successfully developed and implemented the Streamlined Approach For Environmental Restoration (SAFER) method, combining the Observational Method and the principles of the USEPA's Data Quality Objectives (Gianti, 1994:1).

The Observational Method attempts to streamline the remedial investigation phase by addressing the uncertainties associated with characterizing the subsurface geology, hydrogeology, and nature and extent of contamination (Dean and Barvenik, 1992:33). The Observational Method addresses the uncertainties by only exploring sufficiently to establish the most probable conditions and possible deviations from these conditions, then it establishes a remediation design based on the most probable conditions (Peck, 1969:173). To address the possible deviations from the most probable conditions, the Observational Method designs a course of action to implement for every foreseeable deviation and then evaluates actual conditions observed in the field during construction and operation of the initial remedial design (Peck, 1969: 173). If field observations indicate the actual conditions are different than those assumed in the most probable conditions, modifications to the original remedy are implemented (Peck, 1969:173).

There are advantages and disadvantages for both the Observational Method and the traditional Superfund process of site characterization as summarized in Table 2-1. The advantages of the Observational Method are limited up-front investigation and design requirements and usually significantly lower total project costs and duration (Dean and Barvenik, 1992:36). The advantages of the traditional Superfund process are a high degree of certainty when the decision is made that the selected remedy will be the most effective (Dean and Barvenik, 1992:36). The disadvantage of the Observational Method is less certainty that the selected remedy will be the most effective and subsequently create a design that may fail (Dean and Barvenik, 1992:36). The disadvantages of the traditional Superfund process are exhaustive front-end investigation requirements and significantly greater total project costs and duration (Dean and Barvenik, 1992:36).

The second alternative approach, presumptive remedies, attempts to streamline the feasibility study phase of the Superfund process. Presumptive remedies are proven clean-up technologies that can be applied to similar sites, contaminants, or both (USEPA, 1992a:10). The advantage of presumptive remedies is that the lengthy site study and evaluation of treatment technologies are not required when using the technologies which worked well before at similar sites (USEPA, 1992a:10). However, by eliminating or reducing the technologies evaluated during the feasibility study there is less certainty the selected remedy will be the most effective and subsequently create a design that will fail.

Table 2-1

Relative merits of the Observational and Traditional Superfund Process (Dean and Barvenik, 1992:36)

Advantages		Disadvantages	
Observational Method	Superfund Process	Observational Method	Superfund Process
-Limited up-front investigation and design requirements -Significantly lower total project cost and duration	-High degree of certainty most effective remedy is selected	-Less certainty selected remedy is effective	-Exhaustive front-end investigation requirements - Significantly greater total project cost and duration

What Needs To Be Done?

Obviously there is room for improvement of the Superfund process, progress is slow and costs are exorbitant. In order to reduce costs and improve progress, various alternatives to the traditional Superfund process have been proposed as outlined above (Dean and Barvenik, 1992:36 and USEPA, 1992b:10). However, the project managers of sites on the NPL are still faced with determining which approach is preferred for their site. By modeling the decision structure, uncertainties, and preferences, this thesis proposes to develop a decision support model to evaluate and compare the various approaches that will aid project managers in deciding which approach is preferred for the particular situation they are facing.

The USAF has a vested interest in implementing improvements in the remediation process because of the high cost of cleanup and large number of Air Force sites still on the NPL. On 17 April 1991, the Chief of Staff of the Air Force set a goal of finishing 10% of all IRP sites per year with all sites finished by the year 2000 (USAF, 1992:1-1). The Air Force estimates that it will cost an additional $3.8 billion to remediate the 32 installations still on the NPL (DoD, 1992:A-6). If there is an alternative approach that will reduce project duration to help meet the goals set by the Chief of Staff and/or lower the cost, while at the same time meeting the objectives of CERCLA and the IRP, the Air Force should adopt and implement the approach as soon as possible. The decision support model proposed in this thesis will aid the Air Force in identifying the most appropriate policy to adopt.

III. Methodology

Introduction

With both of the alternative approaches, the Observational Method and presumptive remedies, it is not absolutely clear that either process is better than the traditional Superfund process. The alternatives attempt to lower total project cost and duration while increasing the uncertainty of implementing an effective remedy (Dean and Barvenik, 1992:36). The principles of decision analysis provide an effective method of measuring project cost and duration and the effects of the increased uncertainty (Clemen, 1991:2). The first section will briefly discuss the principles of decision analysis to provide the reader a basic understanding of the decision analysis tools used to model the decision problem. Then the decision model used to quantitatively evaluate and compare the alternatives will be defined.

Decision Analysis Theory

Decision Analysis provides structure and guidance for systematic thinking about difficult decisions. It is an information source, providing insight about the situation, uncertainty, objectives and tradeoffs, and possibly yielding a recommended course of action (Clemen, 1991:4). The overall strategy of decision analysis is to decompose a complicated problem into smaller, more manageable elements that can be more readily analyzed (Clemen, 1991:9).

There are three steps in the basic process used to decompose and model the problem. The first step models the problem structure. The structure consists of two parts, the elements influencing the final outcome and the relationships among the elements (Clemen, 1991:34). There are three types of elements: *decisions to make*; *uncertain events*; and *value of specific outcomes* (Clemen, 1991:34).

Decisions to make are elements of the decision that the decision maker has complete control over the alternative selected (Clemen, 1991:17). For example, suppose an investor is trying to decide where to invest his money. He could buy stocks or put his money in a savings account. In this case selecting which vehicle to invest in would be a *decision to make* because the investor has complete control of the vehicle employed.

Uncertain events are factors which effect the final outcome of a decision problem and the outcomes are beyond the control of the decision maker (Clemen, 1991:19). Continuing with the example above, whether or not the stock market went up or down would be an *uncertain event*. The investor has no control of the stock market yet whether or not the stock market goes up or down will affect the future value of his money.

Value of specific outcomes is the final outcome after all the decisions have been made and all the outcomes of uncertain events are known (Clemen, 1991:21). In the above example, the *value of the specific outcomes* is how much money the investor has after he selects a investment vehicle and the outcome of the stock market is known.

In addi

1991:34).

There are two tools used to structure problems; influence diagrams and decision trees, and each tool has different strengths (Clemen, 1991:34). An influence diagram provides a compact representation of the problem, graphically representing the elements of the decision and the relationship among the elements, while suppressing many of the details (Clemen, 1991:56). Decisions to make are represented by squares, uncertain events are represented by circles and the value of outcomes are represented as a square with rounded corners (Clemen, 1991:34). The shapes are connected by arrows, called arcs, to show the relationship among the elements (Clemen, 1991:34).

Decision trees are another tool to graphically represent the structure of the problem. Decision trees display more of the details that remain hidden in an influence diagram (Clemen, 1991:49). Decision trees display the possible decision alternatives on branches emanating from squares and the possible outcomes of uncertain events on branches emanating from circles (Clemen, 1991:49). Value of outcomes are displayed at the end of the last branch (Clemen, 1991:49).

The second step in decomposing and modeling the problem is modeling the uncertainty. One of the central principles in decision analysis is that uncertainty of any kind can be represented through the appropriate use of probability (Clemen, 1991:169). There are several ways to model uncertainty in decision problems by using probability. One of the primary means of modeling uncertainty is quantifying the decision makers subjective believes about the uncertainty (Clemen, 1991:167). Uncertainty can also be modeled by using standard mathematical models, historical data, and computer simulation (Clemen, 1991:167).

The last step in decomposing and modeling the problem is modeling the preferences of the decision maker. Because most decision problems involve some kind of trade-off, it is necessary to model preferences (Clemen, 1991:361). In multiple attribute decision problems with different dimensions of values, utility is the unit of measurement (Chechile and Carlisle, 1991:73). Utility is defined as the perceived worth to the individual decision maker (Chechile and Carlisle, 1991:72).

Decomposing and Modeling the Problem

Structuring the Problem. As mentioned earlier, the first step in the decision analysis process is to construct a model of the decision problem that identifies the elements affecting the final outcome and the relationship among the elements. This thesis will use an influence diagram to represent the elements and their relationships and a decision tree to display the details of the problem. The model structure is presented from the view point of the Remedial Project Manager (RPM) who is responsible for the overall project.

The RPM is responsible for cleaning up the site, but the manager is also concerned with minimizing the total cost and duration of completing the site clean-up (USAF, 1992:2-1). Two alternative approaches were presented that could reduce the overall cost and duration (Einstein, 1991:1773, and USEPA, 1992b:10). However, the alternatives reduce cost and duration while trading off certainty of effectively completing the cleanup (Dean and Barvenik, 1992:36). The problem, from the RPM's viewpoint, is which alternatives offer the best value, where value is measured as the minimum combination of cost and duration. To determine which alternatives present the best outcome, the RPM must determine which factors affect the final cost and duration and the affect uncertainty has on the final outcomes.

There are three processes in the Superfund process which affect the final project cost and duration; the Remedial Investigation, the Feasibility Study, and the Remedial Design and Remedial Action. The final cost is the cost of characterizing the site, identifying a treatment technology to apply, and applying the treatment technology to clean up the site. The final duration is the time required to characterize the site, identify the treatment technology, and the time required to clean up the site. The influence diagram of the Superfund Process, Figure 3-1, captures all the cost and duration values and the uncertainties of these processes.

The development of the decision support model is presented in four phases: Remedial Investigation, Feasibility Study, Remediation, and Value Model. The Remedial Investigation phase captures the elements of the Remedial Investigation Process that affect the final project cost and duration. The Feasibility Study phase captures the elements of the Feasibility Study process that affect the final project cost and duration. The Remediation phase captures the elements of the Remedial Design and Remedial Action processes that affect the final project cost and duration. And the Value Model phase captures the value of the outcomes of the Remedial Investigation, Feasibility Study, and Remediation phases and the preferences of the RPM.

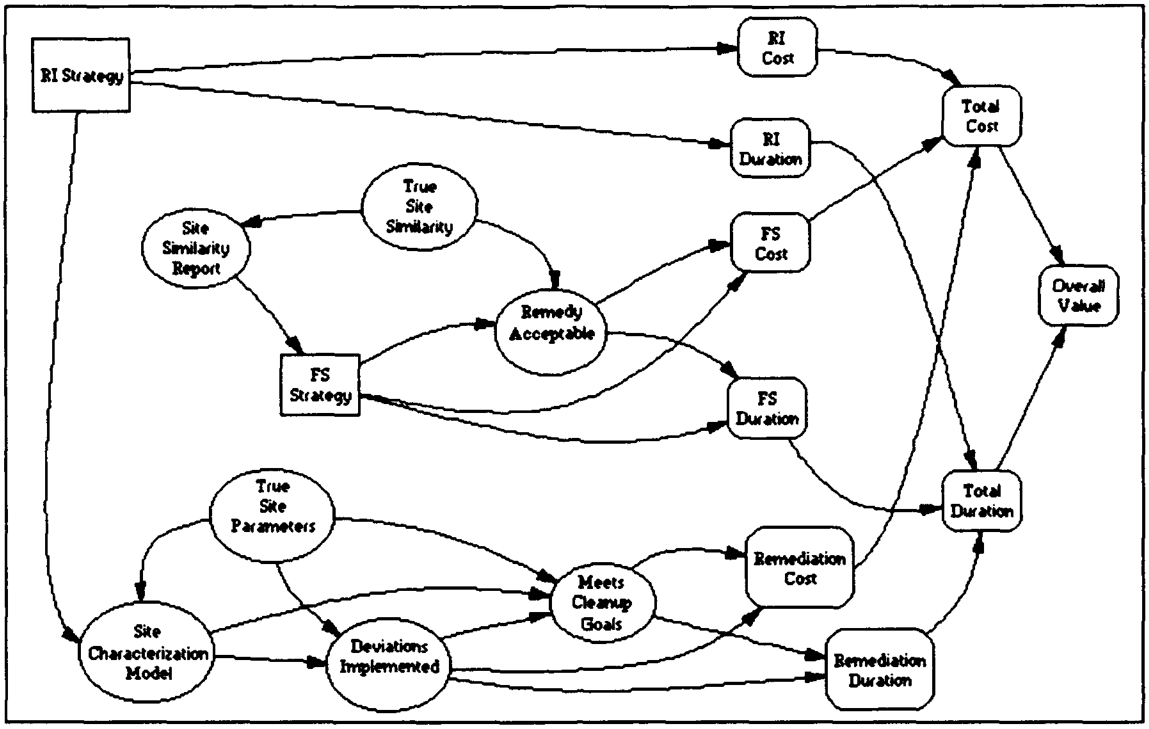

Figure 3-1. Influence Diagram of the Superfund Process.

<u>Remedial Investigation Phase.</u> At the beginning of the Remedial Investigation the results of the Preliminary Assessment and Site Inspection are known to the RPM. If the results of the previous studies warrant a remedial investigation, the RPM has two alternative methods of conducting the RI (Einstein, 1991:1773, and USEPA, 1992b:10). The manager can either implement the Observational Method and design a remedial investigation to *characterize the most likely* site conditions and possible deviations or the manager can implement the traditional site characterization method and *fully characterize* the site to

eliminate as much uncertainty as possible (Dean and Barvenik, 1992:36).

An estimate of the cost and duration of conducting either type of remedial investigation is available to the RPM before deciding which method to implement. Normally the cost and duration required to conduct a remedial investigation by the Observational Method is significantly less than the cost and duration required to conduct the investigation by the traditional method because fewer data points are collected and analyzed (Duplancic and Buckle, 1989:69).

To capture this decision and the uncertainties associated with estimates in the decision model, a series of three nodes is included. A decision node, named **RI Strategy**, captures this decision to make. The RI Strategy node has two alternatives, *Fully Characterize* and *Characterize Most Likely*, corresponding to the options available to the RPM. The estimate of the cost and duration for each alternative is attached to the branches of the respective alternative. Figure 3-2 shows the decision node as represented in the decision tree. The decision tree displays the options as branches emanating from the decision node, represented by the square. Figure 3-2, also displays the cost and duration estimates for each alternative. The estimates are displayed on the underside of the branches.

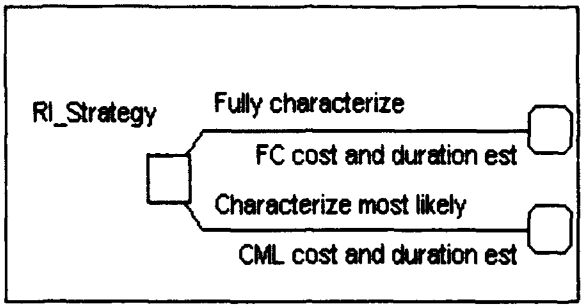

Figure 3-2. The RI Strategy Decision Node as Represented in the Decision Tree.

To capture the cost and duration of completing the remedial investigation regardless of the method chosen, two value nodes are included in the Remedial Investigation Phase of the model, as shown in Figure 3-3. The **RI Cost** node is defined as the final cost of conducting the remedial investigation and the **RI Duration** node is defined as the final duration required to complete the remedial investigation. The arcs from the RI Strategy node, as shown in Figure 3-3, indicate that the final RI Cost and RI Duration are dependent on the alternative chosen.

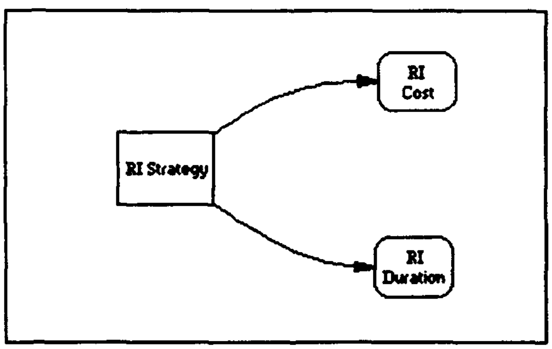

Figure 3-3. The Remedial Investigation Phase as Represented in the Influence Diagram.

Figure 3-4 shows the possible values for RI cost and the possible values for RI duration given the outcomes of RI Strategy. In this case, the chart shows the final values for RI cost and RI duration are the estimates of the chosen alternative.

RI Strategy	RI Cost Value	RI Duration Value
Fully Characterize	Cost Estimate of Fully Characterizing the Site	Duration Estimate of Fully Characterizing the Site
Characterize Most Likely	Cost Estimate of Characterizing the Most Likely Site Conditions	Duration Estimate of Characterizing the Most Likely Site Conditions

Figure 3-4. Possible Outcomes of the RI Cost and RI Duration Nodes.

Feasibility Study Phase. Before designing and implementing a remedy, the RPM must identify and select a treatment technology that will be implemented to remediate the site. The feasibility study process is the method of identifying, evaluating and selecting the most effective treatment technology based on a set of nine criteria (Rudolph, 1993:6-2). As presented earlier, there are two methods of identifying the most effective treatment technology, the traditional Feasibility Study method where all possible technologies are evaluated and the presumptive remedy strategy where only the most likely technologies are evaluated (USEPA, 1992a:10).

If the RPM is interested in pursuing the presumptive remedy strategy, the manager can conduct a study to assess how similar the current site is to previous sites and what technologies were the most successful at these similar sites (USEPA, 1992a:10). This information is critical because it identifies which treatment technologies are most likely to work because they have been previously successful at similar sites (USEPA, 1992a:10). Thus the similarity of the site affects the likelihood of identifying an acceptable remedy if the presumptive remedy option is chosen.

However, there is the possibility the report is incorrect. It is possible the report could indicate the site is similar when in fact it is not similar and it is also possible the report could indicate the site is not similar when in fact it truly is.

After the feasibility studies are conducted to identify the possible remedy, the RPM must select the most appropriate treatment technology. However, if the Presumptive Remedy option is chosen, it is possible that at the end of the feasibility study, no remedy is identified from the limited number of treatment technologies investigated that meet the USEPA's nine criteria for acceptable remedy.

The actual final cost and duration of conducting the feasibility study depends on two events, the type of feasibility study conducted and whether or not an acceptable remedy is identified after the initial feasibility study is concluded. This model assumes that if an acceptable remedy is not identified at the end of the study, the RPM must conduct additional feasibility studies to identify an acceptable one, or demonstrate that there is not one better. These additional studies will increase the cost and duration compared to the original estimates.

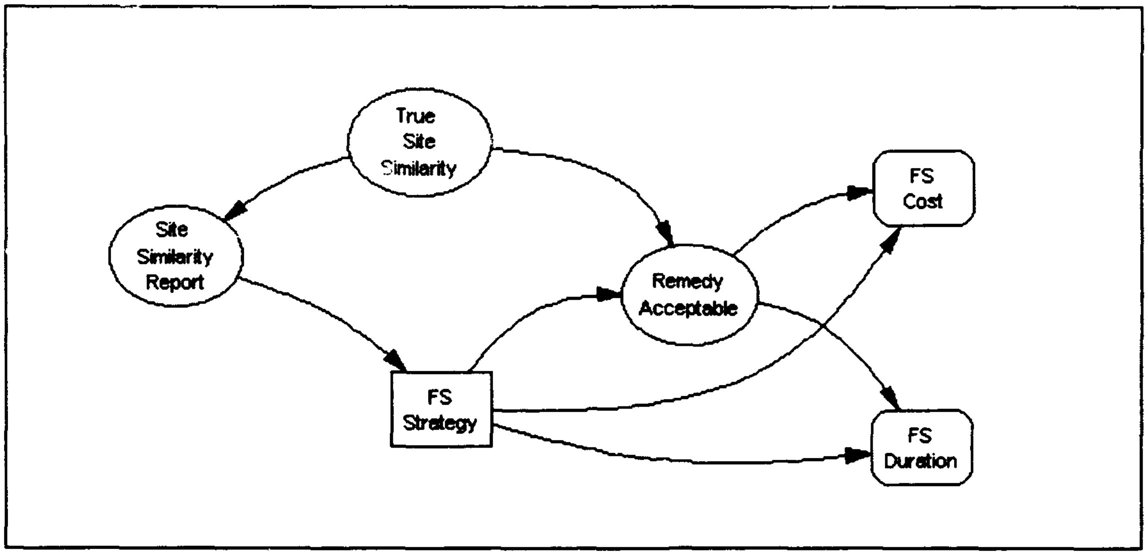

Figure 3-5. The Feasibility Study Phase as Represented in the Influence Diagram.

The model captures the feasibility study phase with a decision node, a series of uncertain event nodes, and two value nodes, as shown in Figure 3-5. The model accounts for the option of selecting the type of feasibility study with a decision node called **FS Strategy**. This node has two alternatives corresponding with the RPMs' options, *Investigate All* and *Presumptive Remedy*. At the time of making the decision, the RPM knows the estimated cost and duration of conducting each alternative. These estimates are included in the decision tree on the branches emanating from the FS strategy node as shown in Figure 3-6.

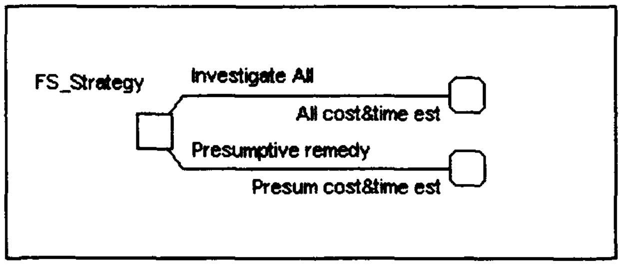

Figure 3-6. Decision Tree of FS Strategy Node.

An uncertain event node called **Site Similarity Report** is used in the model to capture the information that is available to the RPM at the time of making the decision. The arc from the Site Similarity Report node to FS Strategy node indicates this information is available before selecting an alternative. The possible outcomes of this uncertain event are *"Yes"*, the site is similar, and *"No"*, the site is not similar.

However, because there is the possibility the report is incorrect, the uncertain event node called True Site Similarity is included in the decision model. **True Site Similarity** is defined as the likelihood the physical characteristics and conditions of the current site are truly similar to previous successfully remediated sites. There are two possible outcomes for this event, *Similar* and *Not Similar*. Because the outcomes affect the likelihood's of the outcomes of the Site Similarity Report, an arc is drawn to the Site Similarity report node as shown in Figure 3-5.

The model captures the uncertainty of identifying a remedy that meets the USEPA criteria with an uncertain event node called Remedy Acceptable. **Remedy Acceptable** is defined as the likelihood the selected remedy meets the USEPA's nine criteria of an acceptable remedy. This event has two possible outcomes, *Yes* or *No*. Figure 3-7 shows the possible outcomes of Remedy Acceptable given the outcomes of the influencing events, FS Strategy and True Site Similarity.

If the chosen feasibility study does not identify an acceptable remedy, one that meets the nine criteria of USEPA, then additional feasibility studies are required. This model assumes that an acceptable remedy will be identified after additional feasibility studies. These additional feasibility studies will increase the final cost and duration of completing the feasibility study phase. The additional cost and duration are captured by the Remedy Acceptable node, as shown in Figure 3-7.

FS Strategy	True Site Similarity	Remedy Acceptable Outcome	Value
Investigate All	Similar	Yes	Cost and duration estimate of investigating all technologies
	Not Similar	No	Cost and duration estimate of investigating all technologies + cost and duration of additional studies
Presumptive Remedy	Similar	Yes	Cost and duration estimates of investigating presumptive technologies
	Not Similar	No	Cost and duration estimates of investigating presumptive technologies + cost and duration of additional studies

Figure 3-7. Possible Outcomes of the Remedy Acceptable Node.

The actual cost and duration of conducting the feasibility study depends on the type of feasibility study conducted and whether or not an acceptable remedy is identified after the initial feasibility study. To capture the final cost and duration of conducting the feasibility study in the model, two value nodes are included, FS Cost and FS Duration. **FS Cost** is defined as the final cost of conducting the initial feasibility study plus the additional cost if an acceptable remedy is not identified initially. **FS Duration** is defined as the final duration required to conduct the initial feasibility study plus the additional time required if an acceptable remedy is not identified. Because the Feasibility Study option chosen and whether or not an acceptable remedy is identified affect the final cost and duration, arcs are drawn from the FS Strategy node and the Remedy Acceptable node to both of these nodes, as shown in Figure 3-5. Figure 3-8 shows the outcomes of FS Cost and FS Duration given the outcome of FS Strategy and Remedy Acceptable.

FS Strategy	Acceptable Remedy	FS Cost Value	FS Duration Value
Investigate All	Yes	Estimated cost of investigating all technologies	Estimated duration of investigating all technologies
	No	Estimated cost of investigating all technologies + Estimated cost of additional studies	Estimated duration of investigating all technologies + Estimated duration of additional studies
Presumptive Remedy	Yes	Estimated cost of investigating presumptive technologies	Estimated duration of investigating presumptive technologies
	No	Estimated cost of investigating presumptive technologies + estimated cost of additional studies	Estimated duration of investigating presumptive technologies + estimated duration of additional studies

Figure 3-8. Possible Outcomes of the FS Cost and FS Duration nodes.

Remediation Phase. The RPM conducts the Remedial Investigation and the Feasibility Study to design and implement a remedy to achieve the ultimate goal of cleaning up the site to the standards set by the USEPA. The Remedial Investigation produces a site characterization model used to design the remedy (Rudolph, 1993:5-6). The Feasibility Study identifies the treatment technology to use in the remedy (Rudolph, 1993:6-2).

The ability of the remedial action to successfully clean up the site is directly dependent on the remedial design. Therefore, how well the site model accurately depicts the actual site conditions will influence the outcome of the remedial design and thus the outcome of the remedial action. However, because the site model is only an assessment of the actual conditions, there is the possibility the site model is incorrect (Gianti, 1994b). It is possible for the site model to predict one set of conditions when in fact a different set of conditions exist. For example, if the site model predicts the ground water is flowing north when in fact it is flowing south, a pump and treat system designed and installed north of the contaminant plume would not capture the plume, thus the remedy would not work.

The likelihood of the site model accurately describing the true site is affected by the RI strategy chosen. The traditional method of remedial investigation reduces uncertainty of the true site characteristics to the lowest level possible (Dean and Barvenik, 1992:36). However, because the observational method of remedial investigation trades-off uncertainty for lower cost and duration, it produces a site model with a lower level of confidence (Dean and Barvenik, 1992:36).

While the remedy is being installed and operated, the RPM monitors the site for possible deviations in parameters from the original site model as developed from the Remedial Investigation results. If deviations are identified, the RPM can design and implement remedies to address these deviations that the original design was not capable of addressing (Peck, 1969:173). When deviation remedies are implemented the likelihood of the overall site remedy meeting standards are increased because the remedy is based on observed truths (Duplancic and Buckle, 1993:54).

The likelihood of deviations remedies being required is influenced by the remedial design which is ultimately influenced by the accuracy of the site model (Duplancic and Buckle, 1993:54). Deviation remedies are designed to correct the original remedial design when the original remedial design is not sufficient to effectivly clean up the site as a result of errors in the site characterization model (Peck, 1969:173). Therefore, deviation remedies are more likely to be required as the accuracy of the site characterization model compared to the actual site characteristics decreases. If deviations are implemented, the cost and the duration of implementing the deviation remedies will affect the final cost and duration of the remediation phase (Dean and Barvenik, 1992:35).

Once the remedy is completed, it is possible that the remedy will not achieve the cleanup standards set by the USEPA in the ROD. Whether or not the remedy ultimately achieves the cleanup standards is dependent on the accuracy of the site model compared to the true conditions and whether deviations were implemented to correct any deficiencies in the design as a result of the incorrect site model (Duplancic and Buckle, 1993:55). When the site model accurately depicts the true site parameters, the likelihood of meeting goals improves. When Deviation remedies are implemented, the likelihood of meeting the cleanup standards improves.

This model assumes that if the initial remedy does not meet the cleanup standards, the next remedy designed and implemented will meet cleanup standards. The additional Remedial Action will significantly increase the final cost and duration of completing the remediation phase of the project.

To capture the uncertainty of the remedial action meeting cleanup goals and the final cost and duration of implementing the remedial action, a series of uncertain event nodes, and two value nodes are included in the model as shown in Figure 3-9.

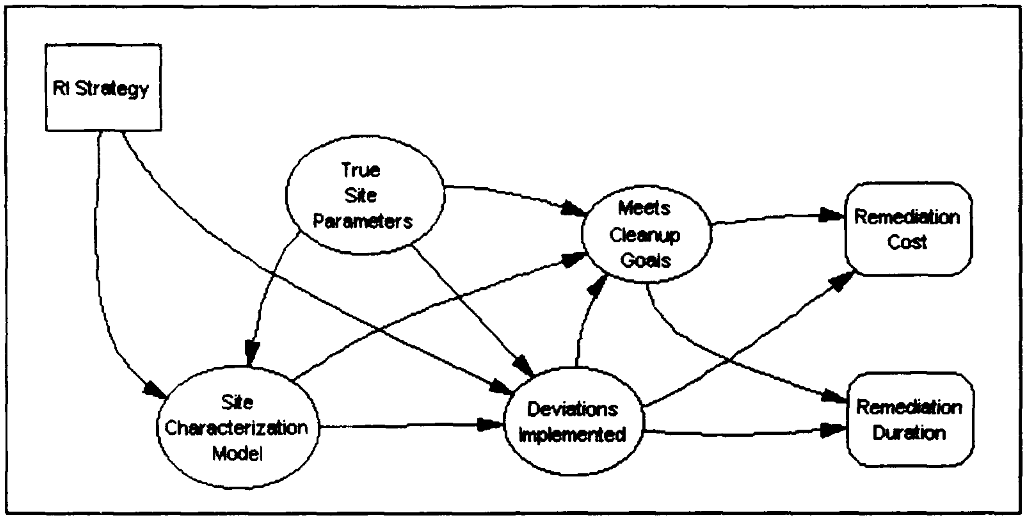

Figure 3-9. Remediation Phase as Represented in the Influence Diagram.

The True Site Parameters node captures the uncertainty of the true characteristics of the site. **True Site Parameters** is defined as the set of parameters that characterize the actual site conditions. For the purpose of this model, the number of possible outcomes of have been reduced from an almost unlimited number at complex sites to just two. The possible outcomes, as shown in Figure 3-10, have been reduced to either *Set A* or *Set B*. All the site parameters are included in each set, but it is assumed that there are only two possible outcomes for each parameter, A or B.

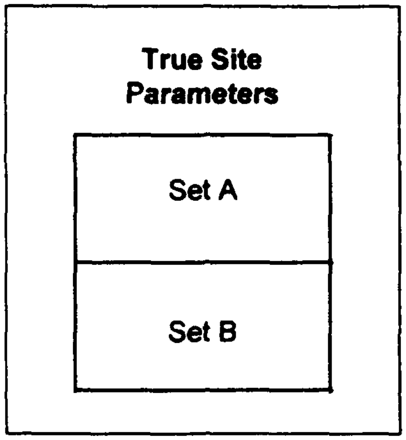

Figure 3-10. Possible Outcomes of the True Site Parameters Node.

The Site Characterization Model node captures the uncertainty of identifying the actual site conditions. The **Site Characterization Model** node is defined as the Site Characterization Model developed from the results of the remedial investigation. The possible outcomes of the Site Characterization Model node are *"Set A"* and *"Set B"*.

The possibility of the model predicting the results of the remedial investigation developing a site model with wrong site characteristics is captured in this node. Figure 3-11 shows the possible outcomes of the Site Characterization Model given the possible outcomes of RI Strategy and True Site Parameters. Figure 3-11, shows it is possible to predict the wrong conditions.

RI Strategy	True Site Parameters	Site Characterization Model
Fully Characterize	Set A	"Set A"
		"Set B"
	Set B	"Set A"
		"Set B"
Characterize Most Likely	Set A	"Set A"
		"Set B"
	Set B	"Set A"
		"Set B"

Figure 3-11. Possible Outcomes of the Site Characterization Model Node.

The likelihood of the site model accurately predicting the true site parameters is affected by the RI strategy chosen and the outcome of the true site parameters. These influences are represented in the model by arcs from RI Strategy and True Site Parameters, as shown in Figure 3-9. The RI strategy influences the likelihood of the Site Characterization Model outcomes because the level of confidence in the Site Characterization Model is lower when the Observational method strategy is chosen. Fully Characterizing the site results in a model with a higher level of confidence that the model accurately predicts the site conditions than the characterize most likely option

(Dean and Barvenik, 1992:36). The actual likelihood's entered into the model are assessed by the RPM and their staff of experts.

The possibility of implementing remedies to correct errors in the remedial design as a result of an inaccurate site model, is captured in the Deviations Implemented node. The **Deviations Implemented** node is defined as deviations from the site model compared to the true site parameters are identified and remedies are implemented as required to correct the original remedial design. Since it is possible that deviation remedies are not implemented when required, there are two possible outcomes for this event, *yes*, deviation remedies are implemented when required, or *no*, deviaition remedies are not implemented when required. Figure 3-12 shows the outcomes of Deviations Implemented given the outcomes for RI Strategy, Site Characterization Model, and True Site Parameters.

The Deviations Implemented node also captures the additional cost and duration of implementing the deviation remedy. Deviation remedies are only required when the Site Characterization Model does not accurately predict the true site parameters. Figure 3-12 shows the additional cost and duration values are only included when the outcome of the event is *Yes*.

RI Strategy	Site Characterization Model	True Site Parameters	Deviations Implemented Outcomes	Values
Fully Characterize	"Set A"	Set A	No	
		Set B	No	
	"Set B"	Set A	No	
		Set B	No	
Characterize Most Likely	"Set A"	Set A	No	
		Set B	Yes	Estimated cost and duration of implementing deviation remedy
	"Set B"	Set A	Yes	Estimated cost and duration of implementing deviation remedy
		Set B	No	

Figure 3-12. Possible Outcomes of the Deviations Implemented Node.

To capture the uncertainty of the selected remedy working and the cost and duration of implementing a remedy that ultimately meets the cleanup standards set by the USEPA the model includes the node called Meets Cleanup Goals. The **Meets Cleanup Goals** node is defined as the likelihood that after the remedial action is completed, the cleanup standards as established in the ROD, are achieved. The possible outcomes are *Yes*, the goals are achieved, and *No*, the goals are not achieved. Figure 3-13 shows the possible outcomes and values of Meets Cleanup Goals given the outcomes of Site Characterization Model, True Site Parameters, and Deviations Implemented. This model assumes that cleanup goals will always be met when the Site Characterization Model accurately predicts the true site parameters or when the Site Characterization Model does not predict the true site parameters but deviation remedies are implemented.

In addition to capturing the likelihood of meeting goals or not, the node captures the estimated cost and duration of designing the remedy and implementing the remedy as initially designed. Also, if the initial remedy does not meet the standards, the RPM must initiate a new design and implement a new remedy, which will increase the cost and duration of the total remediation cost and duration, as shown in Figure 3-13. The node captures this additional cost and duration by adding the estimate for these values to the estimates of the original values. These added values are then assigned only if the remedy does not meet standards.

The Remediation Cost and Remediation Duration nodes capture the final remediation cost and remediation duration. The **Remediation Cost** node is defined as the sum of designing and implementing the initial remedy, implementing deviation remedies, and designing and implementing an additional remedy if required. The **Remediation Duration** node is defined as the sum of the durations required to design and implement the initial remedy, implement deviation remedies, and design and implement additional remedies if required.

Site Characterization Model	True Site Parameters	Deviations Implemented	Meets Clean-up Standards Outcome	Meets Clean-up Standards Values
"Set A"	Set A	Yes	Yes	Estimate of original
		No	Yes	Estimate of original
	Set B	Yes	Yes	Estimate of original
		No	No	Estimate of original + additional remediaition
"Set B"	Set A	Yes	Yes	Estimate of original
		No	No	Estimate of original + additional remediaition
	Set B	Yes	Yes	Estimate of original
		No	Yes	Estimate of original

Figure 3-13. Possible Outcomes of the Meets Cleanup Goals Node.

The actual cost and duration of completing the remediation phase depends on whether or not deviations are implemented, and whether or not the implemented remedy meets the cleanup standards. To capture these influences, arcs are drawn from the Meets Cleanup Goals node and Deviations Implemented node, as shown in Figure 3-9. Figure 3-14 shows the values of Remediation Cost and Remediation Duration given the outcomes of the Meets Cleanup Goals and Deviations Implemented nodes.

Deviations Implemented	Meets Goals	Remediation Cost Value	Remediation Duration Value
Yes	Yes	Estimated cost of initial remedy + estimated cost of deviation remedy	Estimated duration of initial remedy + estimated duration of deviation remedy
	No	Estimated cost of initial remedy + estimated cost of deviation remedy + estimated cost of additional remedies	Estimated duration of initial remedy + estimated duration of deviation remedy + estimated duration of additional remedies
No	Yes	Estimated cost of initial remedy	Estimated duration of initial remedy
	No	Estimated cost of initial remedy + estimated cost of additional remedy	Estimated duration of initial remedy + estimated duration of additional remedy

Figure 3-14. Possible Outcomes of the Remediation Cost and Remediation Duration Nodes.

Value Modeling

To this point, the model captures both of the alternative remediation approaches and the uncertain events which affect the cost and duration of each phase. The model must capture the effects these outcomes have on the cost and duration of completing the entire project. Additionally, the model requires a means of including the preferences of the RPM towards the overall value of the final value.

The reason the RPM would be interested in possibly implementing either the Observational Method and/or presumptive remedies is to lower total project cost and duration. Therefore, the model measures the total cost and total duration to determine the value of the final outcome to the RPM. The overall value is the best combination of the two attributes. The influence diagram of the final model captures the value of the final outcome with a series of value nodes, as shown in Figure 3-15.

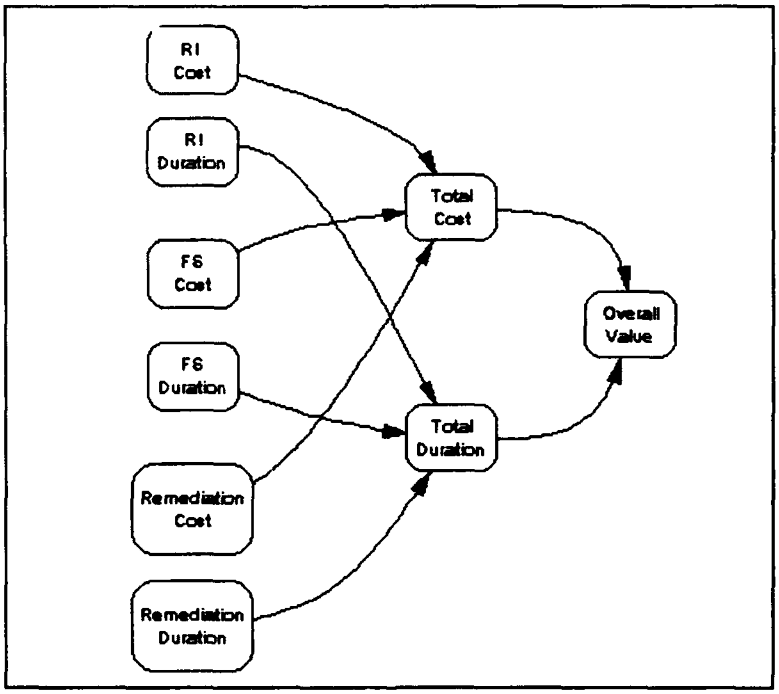

Figure 3-15. The Value Model as Represented in the Influence Diagram.

The Total Cost node, as shown in Figure 3-15, captures the total cost of the project. Total project cost is the sum of the cost of completing the three phases, Remedial Investigation, Feasibility Study, and Remediation. The **Total Cost** node is defined as the sum of the RI Cost node, the FS Cost node, and the Remediation Cost node. The arcs, as shown in Figure 3-15, indicate the final cost is dependent on the outcomes of RI Cost, FS Cost, and Remediation Cost. In the model, cost is measured in thousands of dollars.

The Total Duration node, as shown in Figure 3-15, captures the total duration of the project. Total project duration is the sum of the time required to complete the three phases, Remedial Investigation, Feasibility Study, and Remediation. The **Total Duration** node is defined as the sum of the RI Duration node, the FS Duration node, and the Remediation Duration node. The arcs, as shown in Figure 3-15, indicate the final duration is dependent on the outcomes of RI Duration, FS Duration and Remediation Duration. In the model, duration is measured in months.

The Overall Value node captures the preference of the RPM. The arcs, as shown in Figure 3-15, indicate the overall value is dependent on the outcomes of Final Cost and Final Duration. **Overall Value** is defined as the perceived worth to the RPM given the values of total cost and total duration. Mathematically, Overall Value is defined as

$$\text{Overallvalue} = (\alpha) * U(\text{total cost}) + (1 - a) * U(\text{total duration})$$

Where $\alpha =$ preference factor

$U(\text{total cost}) =$ Utility of total cost

$U(\text{total duration}) =$ Utility of total duration

α quantifies the preference of cost compared to duration of the RPM. For example, if the RPM is equally concerned with the total cost and total duration, then α would equal .5. However, if the RPM is twice as concerned with the total cost because of a fixed budget then with the total duration, then α would equal .66.

In order to relate factors with different units of measurement, the model converts the total cost and total duration into utiles with utility functions in the Total Cost node and the Total Duration node (Checile and Carlisle, 1991:73). The utility functions for total cost and total duration are defined as

$$U(\text{total cost}) = [(-1/\text{max cost}) * \text{total cost}] + 1$$

$$U(\text{total duration}) = [(-1/\text{max duration}) * \text{total duration}] + 1$$

Where

max cost = maximum possible project cost

max duration = maximum possible project duration

The variables max cost and max duration are set by the RPM.

IV. Analysis and Findings

Introduction

The purpose of the RI/FS decision support model is to provide the RPM a means of identifying which method of characterizing the site, the traditional or Observational Method approach, and identifying a treatment technology, the traditional method or Presumptive Remedy approach, should be employed at a particular NPL site. To identify the optimum decision and provide additional insight, this thesis relied on DPL™ to conduct the quantitative analysis of the model. DPL™ is a software package specifically designed for building , analyzing, and conducting sensitivity analysis of decision problems (DPL, 1992:2).

Since the RI/FS decision support model is site specific, values for a representative site scenario were used to validate the decision support model and provide additional insight about the alternative processes. The set of possible input parameters, cost and duration values for each alternative and likelihood values for each uncertain event, were defined based on the current average cost and duration of completing the RI/FS process at the existing Air Force NPL sites (Appendix A).

This chapter first describes the types of analysis conducted on the model and the type of information this analysis can provide. In the next section, the nominal case values used to validate the model are defined. The last section decribes the results of the analysis.

Types of Analysis

Six types of analysis were performed on the decision support model utilizing the built-in DPL™ analysis capabilities. Decision Analysis, the first type, was performed to identify the optimum decision policy. Value Sensitivity Comparison was performed to determine the effect changes in a variable have on the final outcome. Value Sensitivity Analysis was performed on particular variables to examine the sensitivity of the optimal decision policy to changes in a variable. Joint Sensitivity Analysis was performed utilizing the Value Sensitivity Analysis function to examine the sensitivity of the optimal decision policy to changes in two variables simultaneously. Strategy Region Analysis was also performed using the Value Sensitivity Analysis function to define the optimal decision policy given the outcome of two variables. Also, value of information analysis was performed to examine the importance of information prior to making a decision.

In DPL™, the Decision Analysis function calculates the expected value, identifies the optimal decision policy, and displays the Cumalative Risk Profile (DPL™, 1992:303). DPL ™ supplies three outputs when a Decision Analysis is performed on the model. DPL™ determines the expected value (DPL™, 1992:303). DPL™ produces a Decision Policy chart that displays the values and computed outcomes for each decision alternative and identifies the optimum decision alternative for each decision event (DPL™, 1992:306). The optimum decision alternative is the decision alternative with the greatest expected value. DPL™ also produces a chart displaying the cumulative distribution of outcomes for each decision alternative (DPL™, 1992:315).

The Value Sensitivity Comparison function identifies which variables have the greatest effect on the final outcome (Clemen, 1991:116). In DPL™ the Value Sensitivity Comparison calculates the expected value as one particular variable ranges in value while all the other variables remain constant (DPL™, 1992:345). The results are then displayed in a tornado diagram format (DPL™, 1992:345). Tornado diagrams show how much the value of an alternative can vary with changes in the quantity of a specific variable (Clemen, 1991:116).

The Value Sensitivity Analysis function provides an in-depth look at the effects of varying a single variable on the optimum decision policy (DPL™, 1992:339). DPL™ displays the results in a Rainbow diagram (DPL™, 1992:339). The rainbow diagram displays the expected value as a function of the variable being analyzed (DPL™, 1992:341). The rainbow diagram also displays the optimal decision policy and approximates the point at which the optimal decision policy changes (DPL™, 1992:341).

Joint sensitivity analysis utilized the Value Sensitivity Analysis function to examine the effects of varying two variables on the expected value (DPL™, 1992:335). In joint sensitivity analysis one variable is defined as a ratio of another. Joint sensitivity analysis was performed to examine what ratios were required before the optimal decision policy changed.

Nominal Case

As stated previously, the nominal cost and duration values, as shown in Table 4-1, are based on current average Air Force costs and durations. These values were used to validate the model. Table 4-1 lists the nominal cost and duration value followed by the variable name used in the DPL ™ model and the definition of the variables. Table 4-3 lists the nominal likelihood values, variable name used in the DPL™ model, and their definition. Table 4-2 lists the nominal objective function variable values, variable names, and definitions. In this representative scenario, the RPM prefers minimizing duration twice as much as minimizing cost, therefore alpha is equal to .33.

Table 4-1

Nominal Cost and Duration Values

Cost/Duration ($k)/(months)	Variable Name	Definition
3500	FCcost	Cost of implementing the Fully Characterize option
24	FCdur	Duration of Implementing the Fully Characterize option
2000	CMLcost	Cost of implementing the Characterize Most Likely option
12	CMLdur	Duration of implementing the Characterize Most Likely option
2500	ALLcost	Cost of implementing the Investigate All option
24	ALLdur	Duration of implementing the Investigate All option
500	PRcost	Cost of implementing the Presumptive Remedy option
7	PRdur	Duration of implementing the Presumptive Remedy option
2250	RAno cost	Additional cost if Remedy is not Acceptable
22	RAno dur	Additional duration if Remedy is not Acceptable
5000	MCGyes cost	Cost if initial remedy Meets Cleanup Goals
36	MCGyes dur	Duration it initial Remedy Meets Cleanup Goals
4000	MCGno cost	Additional cost if initial remedy does not Meets Cleanup Goals
24	MCGno dur	Additional duration if initial remedy does not Meets Cleanup Goals
1000	DIyes cost	Additional cost if Deviations are Implemented
6	DIyes dur	Additional duration if Deviations are Implemented

Table 4-2

Nominal Objective Function Values

Value	Variable	Definition
$20000 k	max cost	Maximum possible project cost
110 months	max duration	Maximum possible project duration
0.33	alpha	Degree to which miminizing cost is preferred to minimizing duration

Table 4-3

Nominal Likelihood Values

%	Name	Definition
0.65	P(SSR)	Likelihood Site Similarity Report predicts true state
0.75	P(TSS)	Likelihood site is Truly Similar
0.95	P(RA g/all)	Likelihood Remedy is Acceptable given Investigate All
0.75	P(RA g/pr)	Likelihood Remedy is Acceptable given Presumptive Remedy
0.95	P(SCM g/FC)	Likelihood Site Model predicts true state given Fully Characterize
0.6	P(SCM g/CML)	Likelihood Site Model predicts true state given Characterize Most Likely
0.7	P(DI)	Likelihood Deviations are Implemented if required
0.95	P(MCG g/DIyes)	Likelihood Meets Goals given Deviations are Implemented
0.95	P(MCG g/DIno&yes)	Likelihood Meets Goals given Deviations are not Implemented and Site Model predicts true state
0.01	P(MCG gDIno&no)	Likelihood Meets Goals given Deviations are not Implemented and Site Model does not predicts true state
0.5	P(TSP)	Likelihood True Site Parameters are Set A

Analysis and Findings of the Base Decision Model

Decision Analysis of Nominal Case. After all the nominal values were input into the decision model, a Decision Analysis was performed to identify the optimum decision policy and cumulative distribution of possible outcomes. The expected value was .42 utiles. This means if the same scenario, with the same set of nominal values and likelihoods was encountered several times, the average outcome would be .42 utiles. Recall that utiles is the unit of measure for utility and utility is the measure of value perceived by the decision maker. In this case the RPM would receive approximately 42% of the maximum satisfaction possible.

The Decision Analysis, as shown in Figure 4-1, identified the Characterize Most Likely option and Presumptive Remedy option as the optimum decision policy to pursue. This implies the RPM should implement the Characterize Most Likely option, or the Observational Method of site characterization, when deciding which Remedial Investigation strategy to employ in order to maximize utility, or perceived value. Figure 4-1 also shows the optimum decision policy to be the Presumptive Remedy despite the outcome of the Site Similarity Report event. This implies the RPM should implement the Presumptive Remedy approach to identify the appropriate technology. Therefore, the RPM should only investigate the most likely treatment technologies in order to maximize utility.

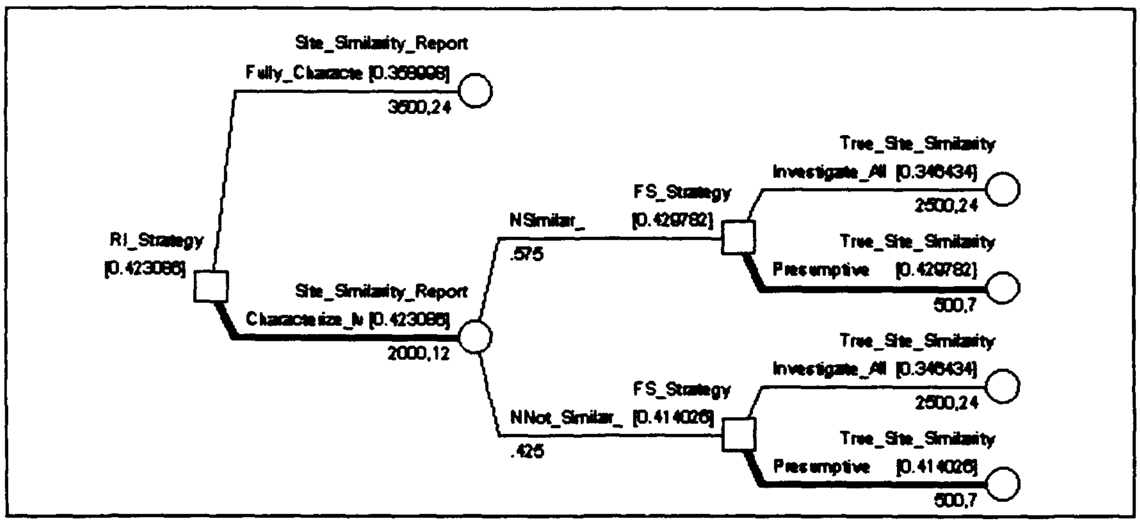

Figure 4-1. Optimal Decision Policy Chart of Nominal Case.

The cumulative distribution chart for the Nominal Case, Figure 4-2 shows the cumulative probability of possible outcomes for each alternative of the RI Strategy decision. In this type of graph, the lower alternative is the better option because there is a smaller probability of getting the same outcome, and the alternative on the right is the better option because there is the same probability of getting a better outcome. Therefore, in this type of graph the alternative that is lower and to the right is the better option.

Most of the time, approximately 90%, as shown in Figure 4-2 the Characterize Most Likely option is lower and to the right of the Fully Characterize option, therefore this option results in a better outcome most of the time. However, this also indicates approximately 10% of the time the RPM would do worse if the manager chooses the Characterize Most Likely option.

The Characterize Most Likely option is below and right of the Fully Characterize option in the Cumaltive Distribution Graph becuase the cost and duration values are much lower for the Characterize Most Likely option. The two areas where the Characterize Most Likely option exceed the Fully Characterize option reflect the increased likelihood that the remedy fails to meet cleanup goals or the remedy is not acceptable. Becuase this portion is small, this indicates the cost and duration savings of the alternative method significantly outweigh the increased uncertainty.

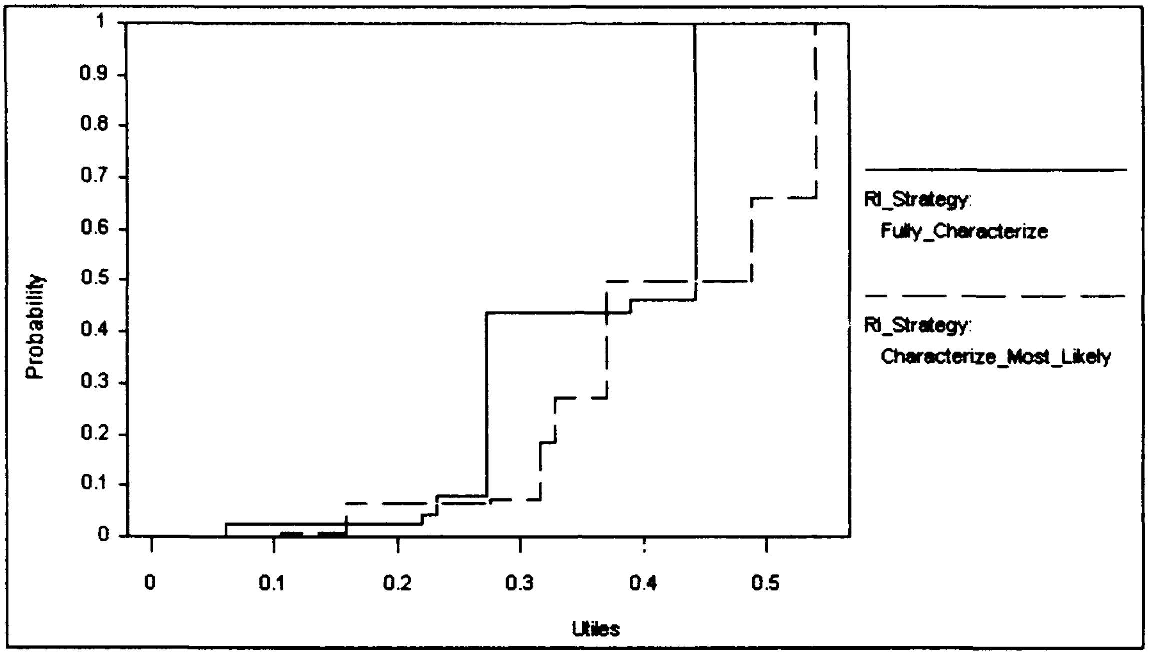

Figure 4-2. Cumulative Distribution Graph for Nominal Case.

<u>Value Sensitivity Comparison of Nominal Case</u>. In order to determine the affect a variable has on the expected value as the variable ranges in value, Value Sensitivity Comparisons were conducted and the results tabulated in tornado diagrams. Separate Value Sensitivity comparisons were completed for the cost and duration variables, Figure 4-3 and for the likelihood variables, Figure 4-4.

Figure 4-3 shows the tornado diagram derived from the Value Sensitivity Comparison of the cost and duration variables. In this type of chart, the width of the bar reflects the affect on the expected value as the value of the variable varies. The variables at the top of the chart have the greatest affect on the final outcome and those variables where the bar changes color indicates the decision policy changes as the value of the variable changes.

Therefore, in this scenario, the top seven variables have a significant impact on the expected value but the decision policy does not change. Whereas, as the values for FCdur, the estimated duration of fully characterizing the site, and ALLdur, the estimated duration of investigating all the possible treatment technologies, vary the expected value does not change significantly but the optimum decision policy changes. Since these variables affect the optimum decision policy, it is worth expending additional resources in order to get a better estimate.

A value sensitivity comparison of the likelihood variables was also completed. The ranges specified for the variables were allowed to vary as widely as practical but remain within reason. Figure 4-4 displays the tornado diagram of the results. The first four likelihood variables have a significant effect on the expected value, however none of the likelihood variables change the optimum decision policy. Further indicating for this scenario, the potential cost and duration savings effect . he optimum decision is much greater then the increased uncertainty effect.

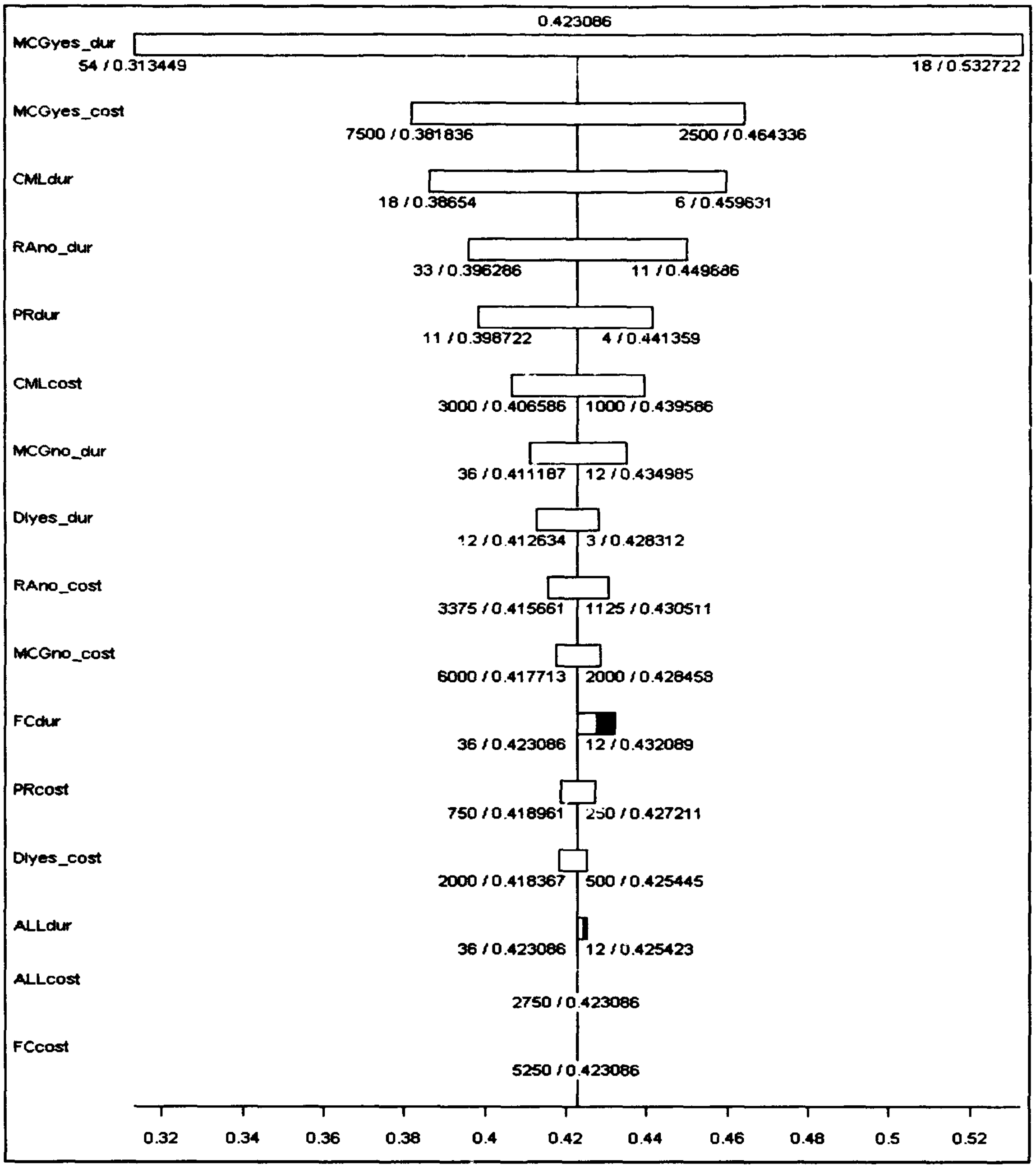

Figure 4-3. Value Sensitivity Comparison of Cost and Duration Variables in the Base Model.

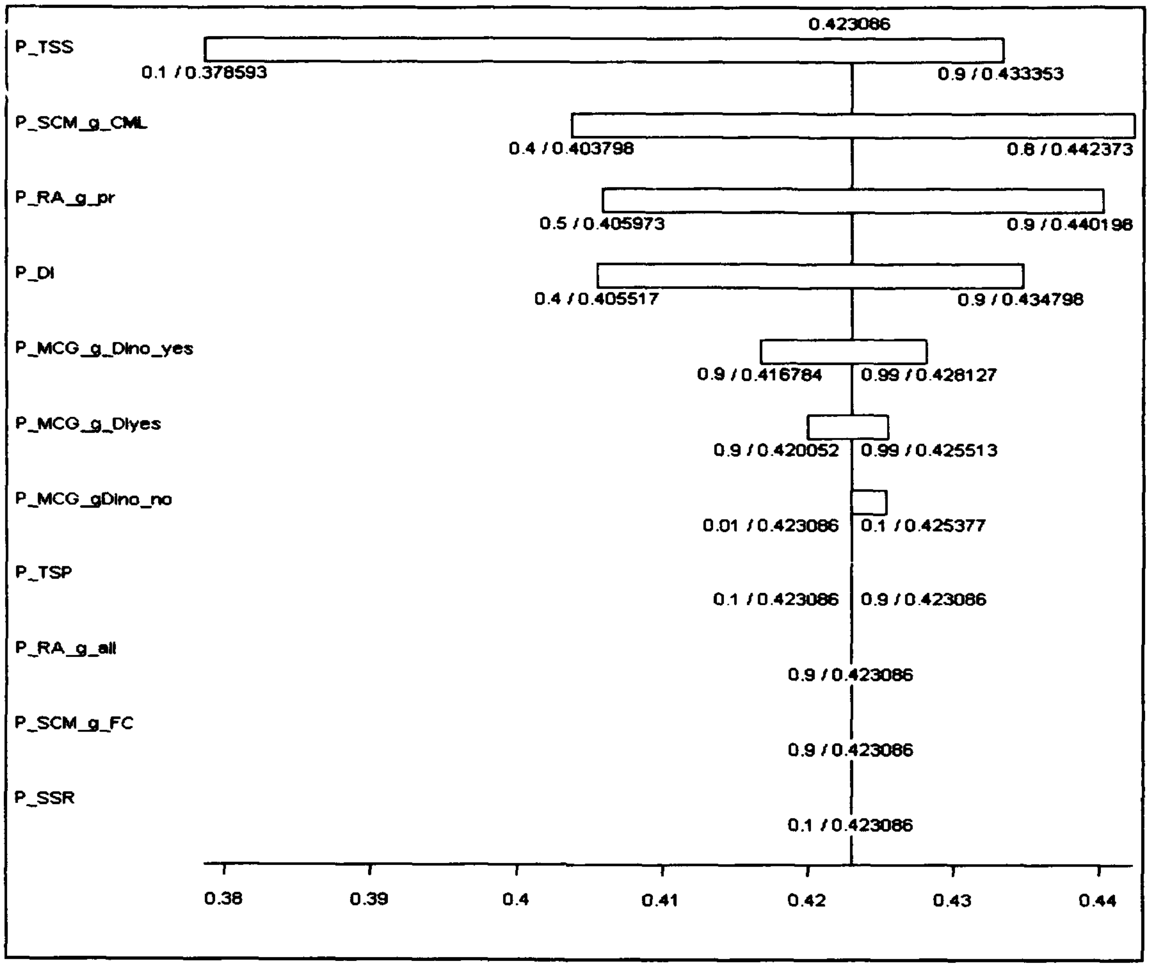

Figure 4-4. Tornado Diagram for the Likelihood Variables in the Base Model.

In addition to conducting a value sensitivity comparison on the cost and duration variables and the likelihood variables, a value sensitivity comparison was conducted on the preference factor, alpha. Alpha was allowed to vary from 1.0 to 0.0 in order to determine if the RPM's preference had any effect on the optimum decision policy. When alpha is equal to one, the RPM prefers to completely minimize cost and when alpha is equal to zero, the RPM prefers to completely minimize duration.

The results, shown in the tornado diagram, Figure 4-5, show that the degree of preference does not affect the decision policy however, it does have a significant affect on the expected valu [illegible] ne RPM, the 13% difference in expected value translates into a 13% increase in satisfaction when the manager prefers to minimize cost only.

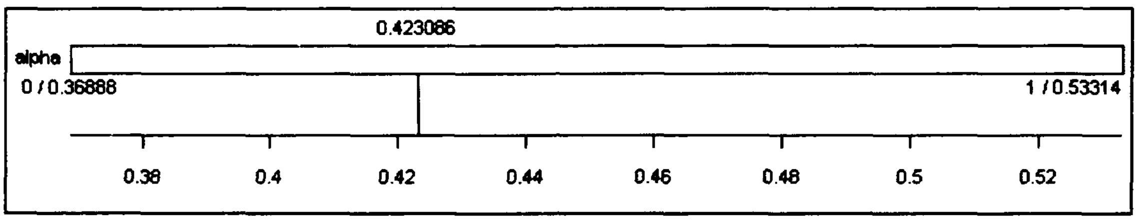

Figure 4-5. Tornado Diagram of Alpha.

<u>Value Sensitivity Analysis of Nominal Case</u>. In order to examine the change in expected value and the optimal decision policy as the significant variables varied, Value Sensitivity Analysis was conducted. In DPL™, the Value Sensitivity Analysis function calculates the expected value as a variable changes in value across a predefined range while holding all the other variables in the model constant (DPL™, 1992:339). DPL™ displays the results of a Value Sensitivity Analysis in a graph called a rainbow diagram. The rainbow diagram displays the expected value as a function of the variable value and identifies the regions

where the optimum decision policy changes by shading the regions differently(DPL™, 1992:341).

The significant variables were identified from the results of the Value Sensitivity Comparison displayed in the tornado diagram. For the purpose of this analysis, ALLdur and FCdur were identified as the significant variables. The results of the analysis for ALLdur and FCdur are displayed in Figures 4-8 and 4-9, respectively.

The rainbow diagram for ALLdur, the duration estimate of investigating all the possible treatment technologies, Figure 4-6, shows that the optimum decision policy changes between 12 and 14 months. Because DPL™ determines the expected value at discrete values over the range of the sensitivity variable, the line separating the regions is drawn at the midpoint between discrete values. In this case, the analysis was conducted using four discrete values; therefore, the diagram indicates the optimum decision policy changes somewhere between 12 and 14.

The estimated duration of the alternative to ALLdur for this scenario, PRdur, was seven months. Therefore, the decision policy did not change until the value began to approach the alternative value.

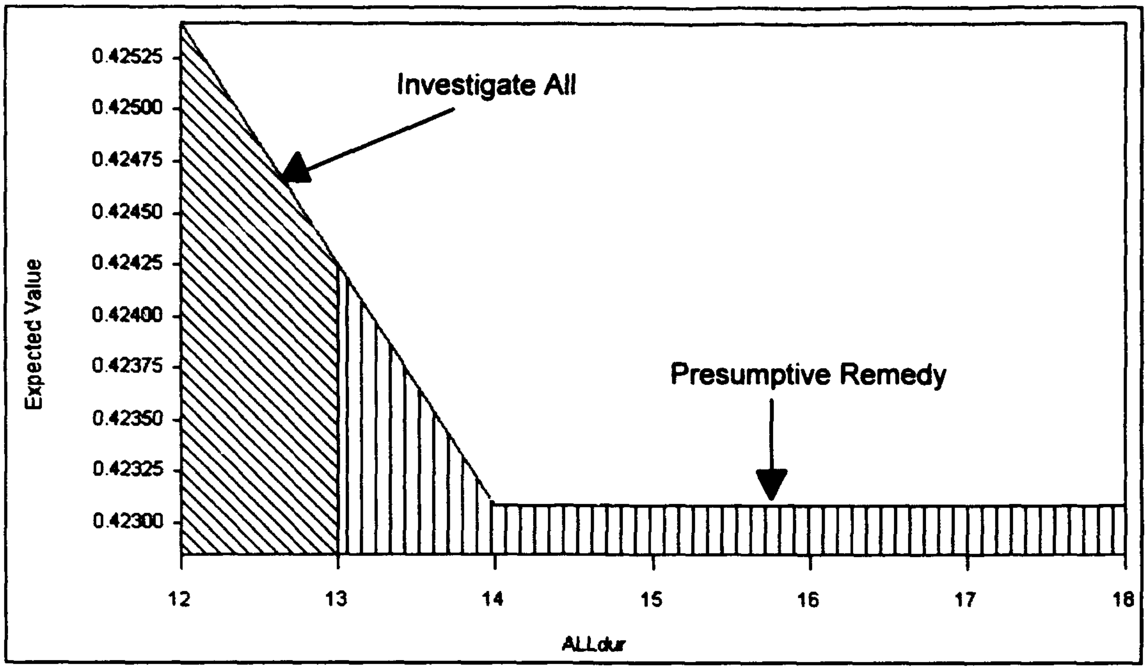

Figure 4-6. Rainbow Diagram of the ALLdur Variable as It Varies From 12 to 18 and Alpha = 0.33.

The rainbow diagram for FCdur, the duration estimate of fully characterizing the site, Figure 4-7, shows that the optimum decision policy changes between approximately 13.2 and 14.7. Again, because of DPL™'s algorithm for conducting the analysis, the optimum decision policy changes somewhere within these bounds.

The estimated duration of the alternative to FCdur for this scenario was 12 months. The decision policy did not change until the value began to approach the nominal duration value for the alternative. Therefore, until the estimated duration of the alternative, characterizing the most likely site conditions, and the estimated duration of fully characterizing are almost equal, the RPM should implement the characterize most likely option.

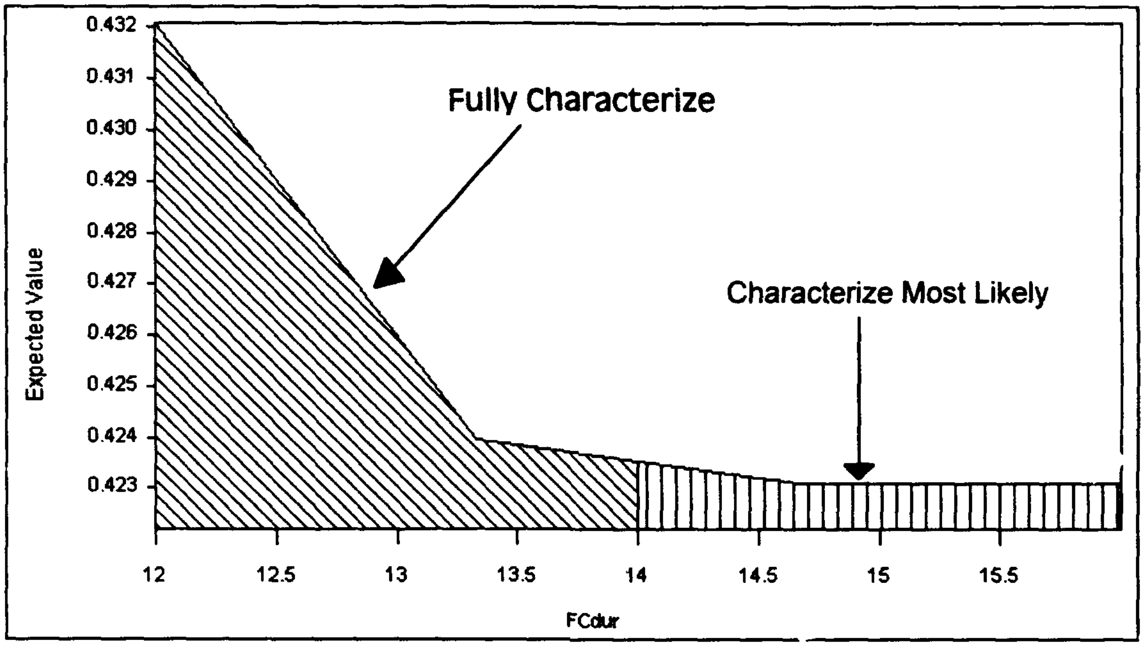

Figure 4-7. Rainbow Diagram of the FCdur Variable as It Varies From 12 to 16 and Alpha is 0.33.

Because the expected value is a function of alpha, the preference of the RPM, the expected value and thus the optimum decision policy will change as alpha varies. If the RPM prefers to minimize duration less, the optimum decision policy cutoff value, as shown in Figures 4-6 and 4-7, will approach closer to the alternative duration.

Analysis and Findings of the Ratio Decision Model

In the ratio model, the base model was modified so that the estimated values of the alternative methods were defined as a ratio of the estimated values of the traditional methods. Therefore, the estimated cost of the Characterize Most Likely option was defined as the estimated cost of the Fully Characterize option multiplied by the RI Ratio, or

CMLcost = FCcost * RI Ratio

And the estimated duration of the Characterize Most Likely option was defined as the estimated duration of the Fully Characterize option multiplied by the RI Ratio, or

CMLdur = FCdur * RI Ratio.

The values for Presumptive Remedy option were similarly defined. All the other cost and duration values and the likelihood values remained the same as the nominal case. The preference factor, alpha was changed to .5 so both cost and duration would have an equal affect on the expected value.

Joint Sensitivity Analysis. To determine the affect on the expected value and the optimum decision policy as cost and duration values for the two decision alternatives varied simultaneously joint sensitivity analysis was conducted on the RI ratio and FS ratio variables in the ratio model. Figure 4-8 shows the results of the joint sensitivity analysis as RI ratio was allowed to vary from .15 to .95. As shown in the Figure, the decision policy changes somewhere between .75 and .85. This implies that the RPM should choose the characterize most likely option when the estimated cost and duration of the characterize most likely option is less then 75% of the estimated cost and duration of fully characterizing the site conditions.

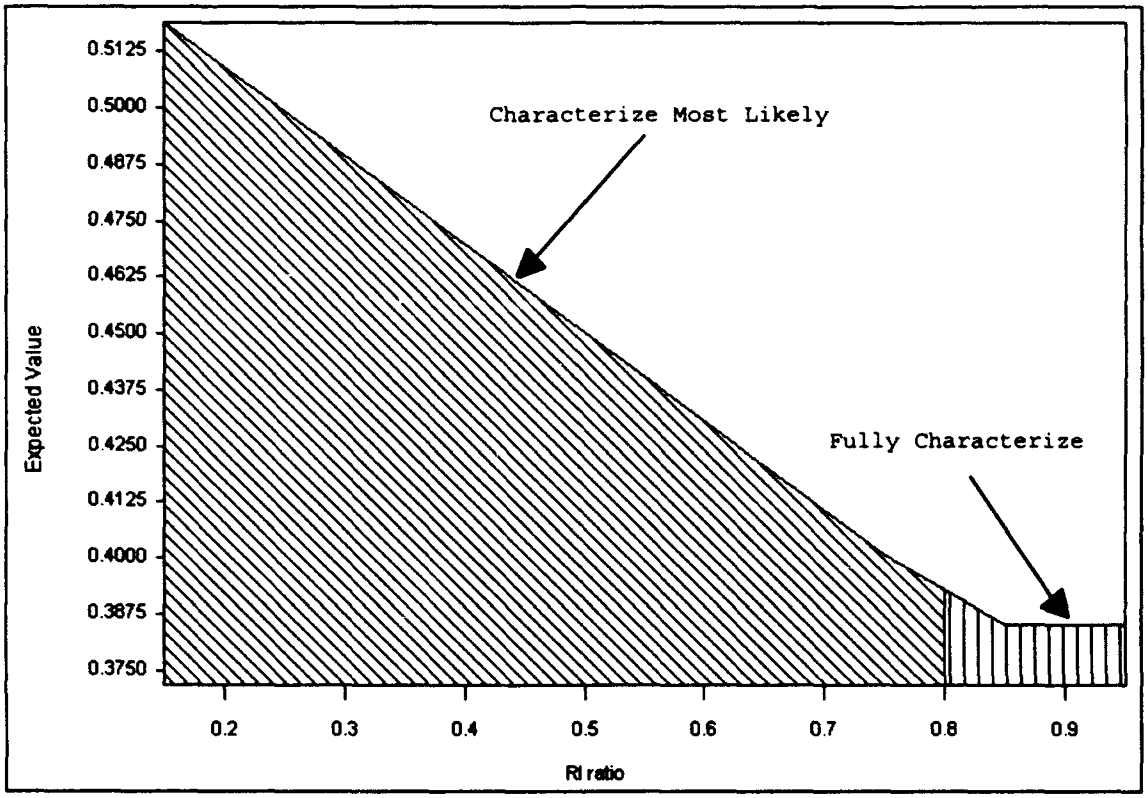

Figure 4-8. Rainbow Diagram of the RI Ratio Variable.

Figure 4-9 shows the results of the joint sensitivity analysis as the FS ratio varied from .15 to .95. As shown in the Figure, the optimum decision policy changes three times, the first change is between .55 and .65 and the second change is between .65 and .75. When the FS ratio is between .55 and .65, optimum decision policy for the FS strategy decision depends on the outcome of the Site Similarity Report, as shown in Figure 4-10.

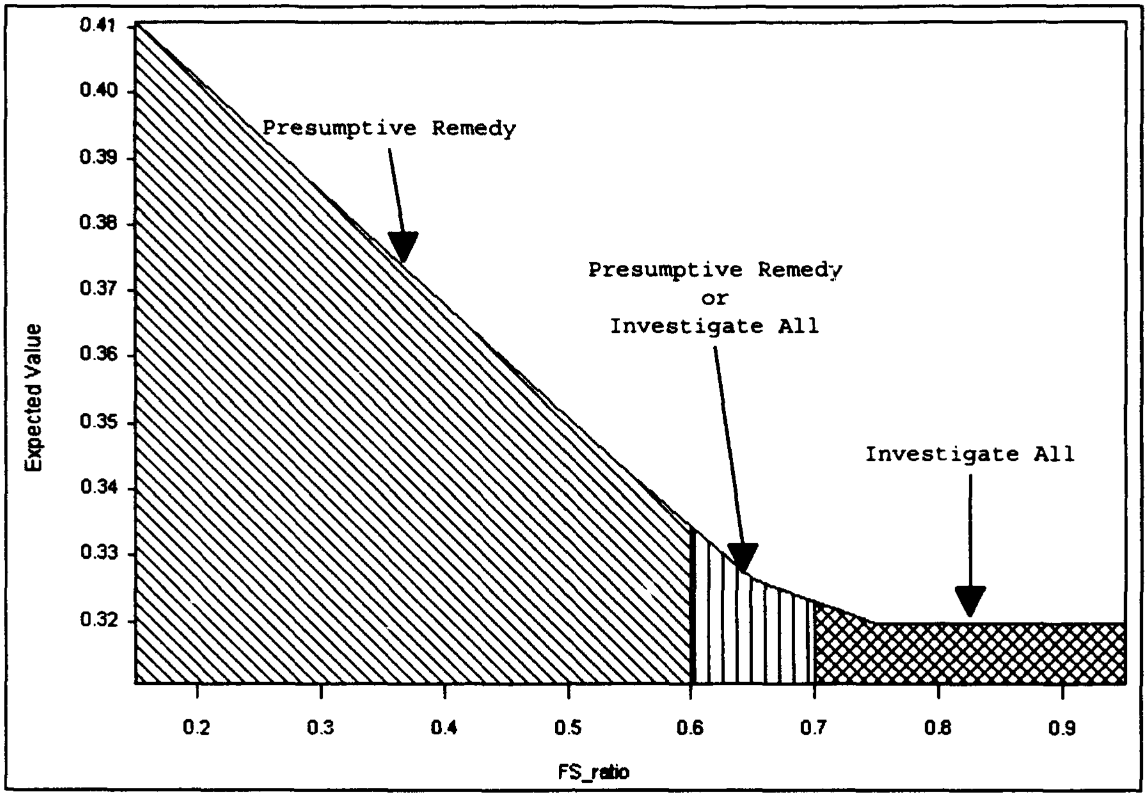

Figure 4-9. Rainbow Diagram of the FS Ratio Variable.

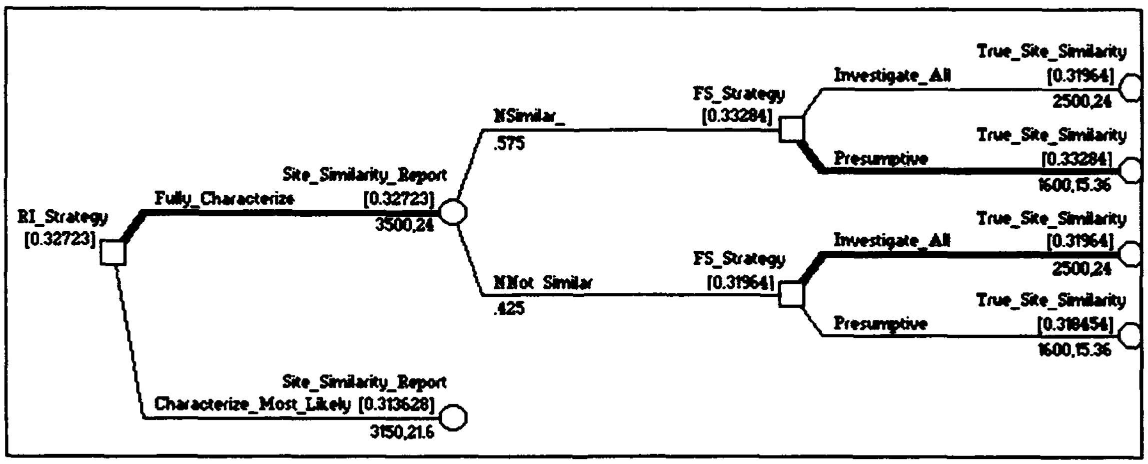

Figure 4-10. Decision Policy Chart of the Ratio Model When RI ratio = .9 and FS ratio = .64.

The results of this analysis implies the RPM's optimal decision policy for conducting the feasibility study will change depending on the degree of savings of implementing the presumptive remedy and the outcome of the Site Similarity report. When the estimated cost and duration of the presumptive remedy option is less then 55% of the estimated cost and duration of the Investigate All option, the RPM should choose to implement the Presumptive Remedy because the cost and duration savings outweigh the increased uncertainty. And when the estimated cost and duration of the presumptive remedy option is greater then 75% of the investigate all estimates, the RPM should choose to implement the investigate all option because the cost and duration savings are not sufficient enough to overcome the potential additional cost and duration associated with the uncertainty of not identifying an acceptable remedy. However, when the estimated cost and duration of the presumptive remedy is between 55% and 75% of the Investigate All estimates, the RPM should base the decision on the outcome of the Site Similarity Report.

Strategy Regions. The joint sensitivity analysis of the Ratio model assumed that both the cost and duration ratio for an alternative were equal and varied at the same rate. To construct the Strategy Regions, the alternative cost ratio and alternative duration ratio were defined independently. Therefore, the estimated cost of the Characterize Most Likely option was defined as the estimated cost of the Fully Characterize option multiplied by the RI Cost Ratio, or

$$CMLcost = FCcost * RI\ Cost\ Ratio.$$

And the estimated duration of the Characterize Most Likely option was defined as the estimated duration of the Fully Characterize option multiplied by the RI Duration Ratio, or

$$CMLdur = FCdur * RI\ Duration\ Ratio.$$

The values for the Presumptive Remedy option were similarly defined. Table 4-4 summarizes the cost and duration ratio variables used to construct the strategy regions.

The Strategy Region analysis was conducted by completing a Value Sensitivity Analysis of one ratio value while the other ratio was set at a fixed value and the point where the optimum decision policy changed recorded. This analysis was repeated several times with the fixed ratio value set at a different level each time.

For example, a Value Sensitivity analysis of the RI Duration Ratio was completed with the RI Cost Ratio set at 1.0. The optimum decision policy changed when the RI Duration Ratio was equal to .69. Then another Value

Sensitivity Analysis was completed with the RI Cost Ratio set at .9. Again the optimum decision change point was recorded. This process was repeated several times until there was no change in the optimum decision policy.

Table 4-4

Cost and Duration Ratio Variables

Ratio Variable	**Definition**
RI Cost Ratio	$\text{RI Cost Ratio} = \dfrac{\text{CMLcost}}{\text{FCcost}}$
RI Duration Ratio	$\text{RI Duration Ratio} = \dfrac{\text{CMLdur}}{\text{FCdur}}$
FS Cost Ratio	$\text{FS Cost Ratio} = \dfrac{\text{PRcost}}{\text{ALLcost}}$
FS Duration Ratio	$\text{FS Duration Ratio} = \dfrac{\text{PRdur}}{\text{ALLdur}}$

After the Value Sensitivity Analysis of the RI Duration Ratio and the FS Duration Ratio was completed for several levels of RI Cost Ratio and FS Cost Ratio, a Strategy Region Graph was completed by plotting the points where the optimum decision changed on an X-Y plot. A Strategy Region Graph shows regions of possible values for which different strategies are optimal (Clemen, 1991:125). Figures 4-11 and 4-12 are the Strategy Region Graphs for the RI Strategy and the FS Strategy decision nodes, respectively.

Figure 4-11 shows that for those combinations of RI Cost Ratio and RI Duration Ratio that fall in the shaded region, the Fully Characterize option is the optimal decision policy. And for those combinations that do not fall within the shaded region, the Characterize Most Likely option is the optimal decision.

For example, given the nominal values for the Fully Characterize option, if the cost estimate of the Characterize Most Likely option is $2800 k, the RI Cost Ratio is 0.8, and if the duration estimate is 21 months, the RI Duration Ratio is 0.88. These values correspond with point **A** in Figure 4-11. Therefore, Fully Characterize is the optimal decision policy. However, if the cost estimate of the Characterize Most Likely option is $2800k and the duration estimate is 17 months, the RI Cost Ratio is 0.8 and the RI Duration Ratio is 0.71. These values correspond with point **B** in Figure 4-11. Therefore, Characterize Most Likely is the optimal decision.

The RI Strategy Region Graph also shows that when the other variables are equivalent to those used in the base model and the preference factor is .5, the Fully Characterize option is the better decision for a small portion of the possible combinations of Characterize Most Likely cost and duration values. This indicates the cost and duration savings of the alternative method of site characterization, the Observational Method, outweigh the increased uncertainty most of the time.

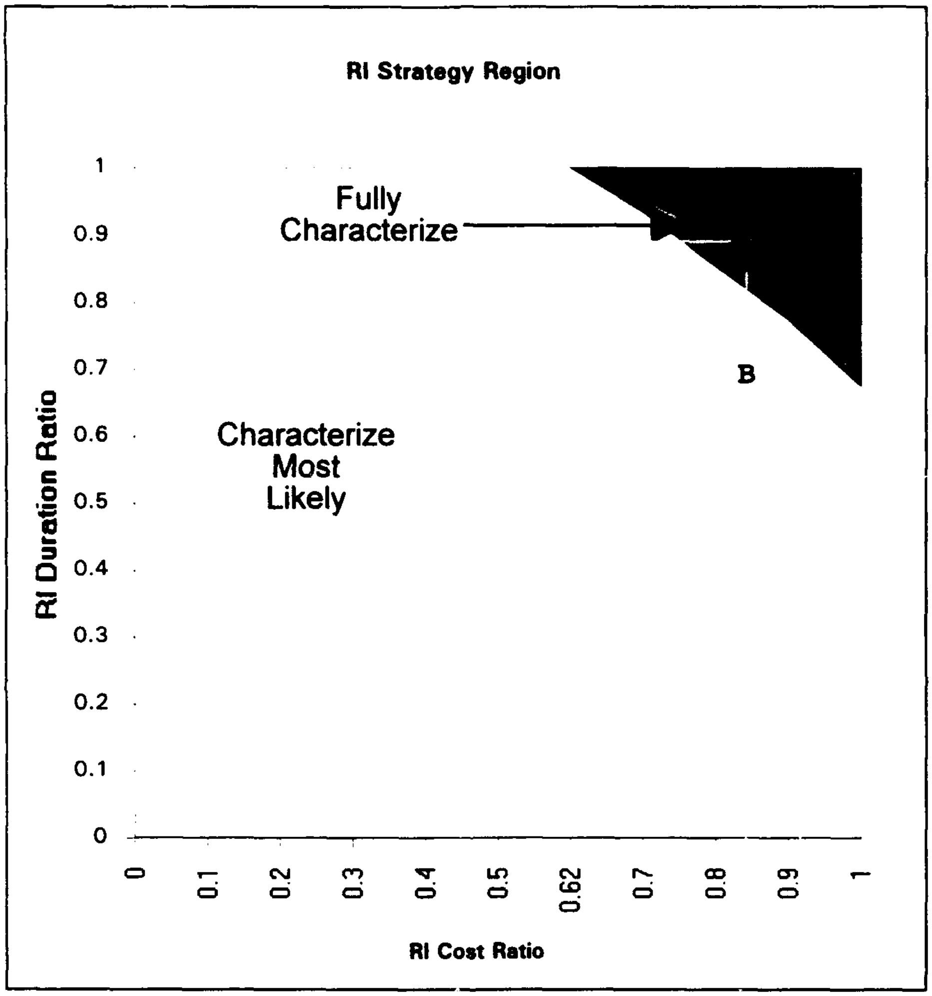

Figure 4-11. Strategy Region Graph for the RI Strategy Node.

The Strategy Region Graph for the FS Strategy node, Figure 4-12, provides similar information. The graph defines the optimal decision policy for given values of FS Cost Ratio and FS Duration Ratio. However, for those combinations in the gray region, labeled Investigate All or Presumptive Remedy, the optimal decision policy depends on the outcome of the Site Similarity Report node.

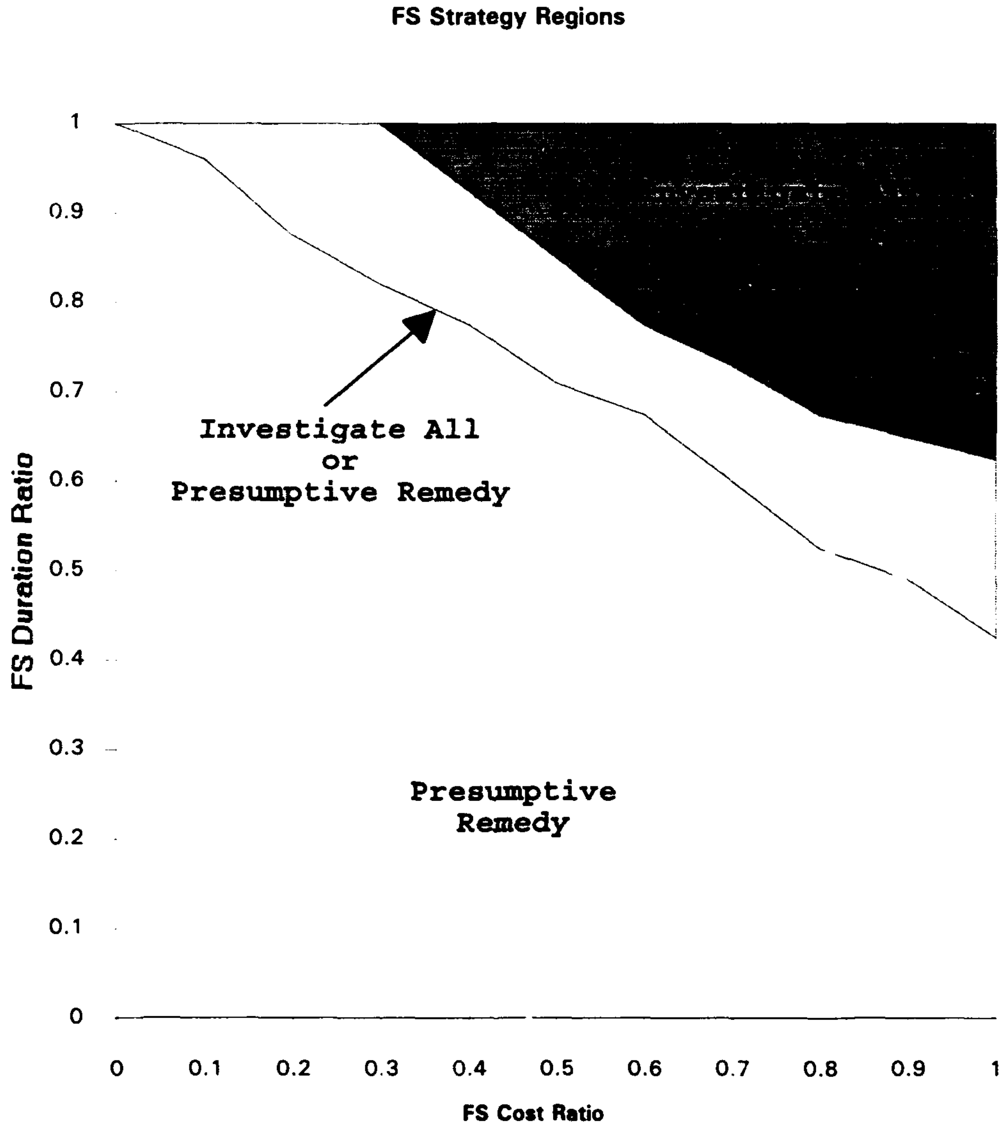

Figure 4-12. Strategy Region Graph for the FS Strategy Node.

The Decision Policy chart for FS Cost Ratio of .6 and FS Duration Ratio of .75, points within the gray region, Figure 4-13, demonstrates that the optimal decision is dependent on the outcome of the Site Similarity Report.

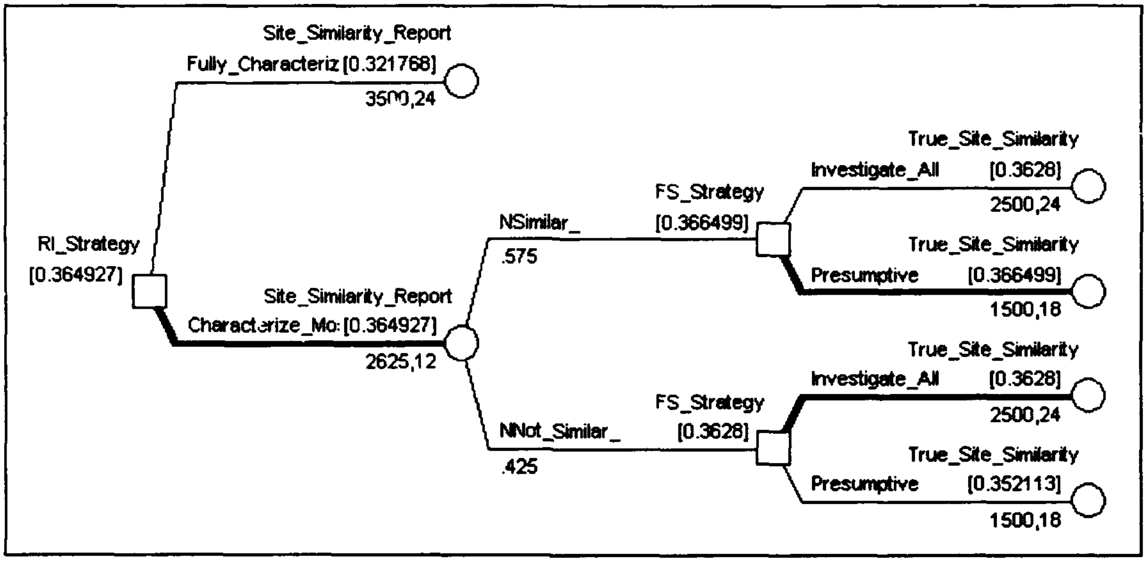

Figure 4-13. Decision Policy Graph When FS Cost Ratio is .6 and FS Duration Ratio is .75.

The FS Strategy Region Graph also shows that when the other variables are equivalent to those used in the base model and the preference factor is .5, the Investigate All option is the better decision for a smaller portion of possible combinations of the Presumptive Remedy cost and duration values. This also indicates the cost and duration savings of the alternative method of identifying a treatment technology, the Presumptive Remedy approach, outweigh the increased uncertainty most of the time.

Value of Information Analysis. A value of information analysis was conducted on four different case scenarios to determine how much money and time information events are worth to the RPM. Information is valuable to the decision maker when it leads to a different decision or when the expected value is higher with the information (Clemen, 1991:342). The Site Similarity Report event is the only event in the decision support model that provides information to the RPM prior to making a decision. As defined earlier, the Site Similarity Report is the results of an expert assessment as to whether or not the current site is similar to previous successfully remedied sites.

The expected value of information is the expected value with prior information minus the expected value without prior information (Clemen, 1991:342). There are two types of information, perfect and imperfect. The expected value of perfect information (EVPI) is the expected value of the model when the outcome of an uncertain event is known prior to a decision (Clemen, 1991:342). In this case, EVPI is the expected value if the Site Similarity Report event could accurately predict the true site similarity 100% of the time. To determine the EVPI, the expected value was determined with the outcome of the uncertain event, the True Site Similarity, known before the decision.

The expected value of sample information (EVSI) is the expected value when the prediction of the outcome of an uncertain event is not perfect. In this case, EVSI is the expected value when the results of the Site Similarity Report are known prior to the decision. To determine the expected value of sample information, the expected value was determined with only the outcome of the information event, the Site Similarity Report, known before the decision.

Since value of information analysis compares the expected value with information and the expected value with no information known prior to the decision, the expected value with no information (EVnoI) was also determined. To determine the expected value of no information, the expected value was determined without the Site Similarity Report event included in the model and the outcome of the True Site Similarity event not known until after the decision.

The value of both perfect and imperfect information was determined for four different cases of the ratio model. Table 4-5 displays the case scenarios; the expected values of perfect, imperfect and no information; and the value of perfect and imperfect information, and the optimum decision policy for each case. For cases #1, #3, and #4, there was no value to either prefect or imperfect information, because the outcome of the information does not affect the decision. Therefore, for these case scenarios, the RPM should not commit any resources to conduct a site similarity study.

Only for case #2 where the optimum decision policy is affected, does the information have any value, as shown in Table 4-6 When the inputs are 0.9 and 0.64 for the RI ratio and FS ratio, receptively, the value of perfect information is 0.00994 utiles and the value of imperfect information is .0005 utiles. To put this in perspective, both the percentage of expected value with no information and the equivalent cost when alpha = 1.0 was calculated, as shown in Table 4-6. If the available information was perfect, the RPM could improve the expected value of no information by 3.04%. But since the information is not perfect, the RPM could only improve the expected value of no information by 0.15%.

Equivalent cost was another measure used to provide a perspective of the utility measurement of the value of information. The equivalent cost is the overall cost that would be equivalent to the value of information measured in utility units. In order to equate the utility to dollars it was assumed that the RPM completely preferred to minimize cost so that alpha = 1.0. As shown in Table 4-6, the equivalent cost of the EVPI was $198.8k and EVSI was $10.0k. Therefore, if the RPM was only concerned with minimizing cost for case scenario #2, the RPM should spend no more than $10k for the Site Similarity Report, since that is all the report will improve the expected value.

Table 4-5

Value of Information Analysis Results

Case	**#1**	**#2**	**#3**	**#4**
Variable Values	RI ratio =.9 FS ratio =.3	RI ratio =.9 FS ratio =.64	RI ratio =.9 FS ratio =.8	RI ratio =.6 FS ratio =.3
EVPI	0.38507	0.33667	0.31964	0.43044
EVSI	0.38507	0.32723	0.31964	0.43044
EVnoI	0.38507	0.32673	0.31964	0.43044
Value of perfect information	0.0	0.00994	0.0	0.0
Value of imperfect information	0.0	0.0005	0.0	0.0
Decision Policy	Fully characterize and Presumptive	Fully characterize and Presumptive or Investigate All	Fully characterize and Investigate All	Characterize Most Likely and Presumptive

Table 4-6

Value of Information for Case #2

	Utility (Utiles)	**Percentage of EVnoI** (%)	**Equivalent Cost** ($k)
EVPI	0.33667		13,266.6
EVSI	0.32723		13,455.4
EVnoI	0.32673		13,465.4
Value of perfect information	0.00994	3.04	198.8
Value of imperfect information	0.0005	0.15	10.0

V. Conclusions and Recommendations

Overview

When CERCLA was passed, Congress did not anticipate the large number of hazardous waste sites requiring remediation. The process required for NPL sites has proved to be quite time consuming and costly. The average NPL remediation project in 1993 cost $25 million and required 10 years to complete. The Air Force is experiencing higher costs and longer process just to complete the RI/FS process. As of 1992, the Air Force has not completed cleanup at any of their NPL sites and the average cost of completing the RI/FS process was over $13 million and required more then 4 years to complete.

Critics point to the process as the cause of long cleanup time and excessive costs. As a result, the Observational Method has been proposed as an alternative approach to characterizing the site conditions and the presumptive remedy method has been proposed as an alternative approach to identify an effective treatment technology. The advantages of both approaches are reduced project costs and duration. However, both approaches trade off lower cost and duration for increased uncertainty.

The primary objective of this thesis was to provide the RPM with a tool to identify if and when these alternative remediation processes are preferred to the traditional processes. To accomplish this objective, this thesis created a decision support model utilizing the DPL™ software package. The decision support model was created by modeling the structure, the uncertainty and preferences of the decision problem, with an influence diagram and decision tree as described in chapter 3.

After the decision support model was defined in DPL™, DPL™'s analysis functions were used to identify the optimum decision policy and provide additional insight for a representative scenario. The values for the representative scenario were based on the average cost and duration of conducting the RI/FS at the 32 NPL sites as of 1992. Additionally, a second model, with the cost and duration values of the alternatives defined as a ratio of the values of the traditional methods, was analyzed.

Summary of Findings

Several conclusions about the specific representative scenario used to test and validate the model can be drawn from the results of the analysis and of the decision support model in general. First, based on the maximum expected value, the preferred alternatives can be identified. This research does not claim the alternative methods are better for every remediation project, but for the scenario tested both alternative methods proved to be the optimum decision policy.

The strategy region analysis clearly showed that the potential cost and duration savings of the alternative processes outweighed the increased uncertainty. Therefore, it is recommendation of this research that the Air Force adopt a flexible policy and use this model to identify the preferred method for each project.

The decision support model captures the preference of the RPM minimizing cost versus duration. For the scenario tested, the RPM's preference influenced the expected value but did not affect the optimum decision policy. As long as both the cost and duration values of the alternative methods were lower than the values for the traditional methods, the RPM's preferences will not affect the optimum decision policy.

Sensitivity analysis can identify those variables that significantly affect the expected value and change the optimum decision policy. For the scenario tested, several variables had a significant affect on the expected value but only two variables changed the optimum decision policy. However, value sensitivity analysis of the ratio model indicates the decision policy does not change until the values of the traditional method approach the values of the alternative methods.

Value of information analysis that the decision support model is capable of conducting can identify the amount of resources worth committing to investigating the similarity of the site to previous sites. For this scenario, investigating the site similarity can increase the expected value slightly, but only when the FS ratio is between .55 and .65.

Future Research

Although the decision support model is very useful in its present form, future research is needed to adapt the model for use with more common software. DPL™ is not in widespread use by RPMs. The model could be modified so that it was spreadsheet based. In addition to using more common software, the model could be modified to be more user friendly.

In its current form, the decision support model does not specifically address the risk attitude of the RPM. The RPM can express fear of project failure during the subjective assessment of the likelihood variables. However, future research could modify the model to quantify the RPM's risk attitude and represent the risk attitude in the objective function.

The current model was validated with values and likelihood's from a representative scenario. Future research could validate the model with data from actual remediation projects.

Future research could also expand the model to eliminate the assumptions of the current model. Currently, the model assumes the site characterization parameters can be grouped into one of two sets. Future research could capture the uncertainty of accurately characterizing each site characterization parameter and the influence each parameter would have on the likelihood of deviations being implemented and the remedy meeting cleanup goals. The model also assumes that if the initial investigation does not identify an acceptable remedy and if the initial remedy does not meet cleanup goals, that subsequent investigation or remedy will always identify an acceptable remedy or meet the cleanup goals. Future research could capture the uncertainty of additional investigation identifying an acceptable remedy and the uncertainty of additional remediation meeting the cleanup goals.

The decision analysis principles used in this research proved to be a sound tool to compare and evaluate the lower project cost and duration and higher uncertainty associated with the alternative methods with the project cost and duration and uncertainty associated with the traditional methods. These principles could easily and effectively be applied to other areas of hazardous waste site remediation. A tool could be developed that focuses only on the site characterization aspect and uses the value of information principle to identify when the site has been sufficiently characterized to proceed with remediation. In addition to Decision Analysis theory, the principles of Multi-Criteria Decision Making could be used to develop a decision support model for selecting the best treatment technology.

Appendix A (DoD, 1992)

USAF Installations Proposed for or Listed on the NPL
Status as of 31 Sep 91

Installation	State	HRS Score	PA/SI Status	PA/SI Year	RI/FS Status	RI/FS Year	Years in RI/FS	RI/FS $(K) thru FY91	Total $(K) thru FY91	Estimated Additional $(K)
AFP #4	TX	39.92	C	84	I	86	5	7,315	14,700	32,370
AFP PJKS	CO	42.93	C	86	I	88	3	1,731		
Castle AFB	CA	37.93	C	83	I	86	5	16,198	29,594	86,464
Dover AFB	DE	35.89	C	83	I	87	4	6,425	8,967	20,910
Edwards AFB	CA	33.62	C	82	I	86	5	26,689	41,000	49,500
Eielson AFB	AK	48.14	C	82	I	86	5	9,643	16,500	10,000
Ellsworth AFB	SD	33.62	C	85	I	87	4	4,655		
Elmendorf AFB	AK	45.91	C	83	I	86	5	7,622		
Fairchild AFB	WA	31.98	C	85	I	88	3	11,777	19,976	59,100
F.E. Warren AFB	WY	39.23	C	85	I	91	0	3,483	11,278	55,000
George AFB	CA	33.62	C	86	I	86	5	4,167	13,237	60,000
Griffiss AFB	NY	34.2	C	81	I	91	0	26,097	37,078	37,600
Hill AFB	UT	49.94	C		I	85	6	16,480	22,627	400,000
Homestead AFB	FL	42.4	C	86	I	87	4	3,456	4,650	16,000
Loring AFB	ME	34.49	C	84	I	86	5	16,491	41,951	282,552
Luke AFB	AZ	37.93	C	85	I	86	5	5,716	9,000	1,500
March AFB	CA	31.94	C	84	I	86	5	8,826	26,158	120,000
Mather AFB	CA	28.9	C	82	I	84	7	28,416	33,860	143,890
McChord AFB (#1)*	WA	42.24	C	86	I	90	1	11,524	15,417	21,100
McChord AFB (#2)*	WA	31.94	C		C	91	0		included above	
McClellan AFB	CA	57.93	C		I	84	7	41,018	72,783	1,580,000
Mountain Home AFB	ID	57.8	C	86	I	85	6	2,866		
Norton AFB	CA	39.65	C	82	I	86	5	12,261	18,600	64,400
Otis ANG Base	MA	45.92	I	86	I	91	0	25,449	29,000	96,000

USAF Installations Proposed for or Listed on the NPL (Continued)
Status as of 31 Sep 91

Installation	State	HRS Score	PA/SI Status	PA/SI Year	RI/FS Status	RI/FS Year	Years in RI/FS	RI/FS $(K) thru FY91	Total $(K) thru FY91	Estomated Additional $(K)
Tinker AFB	OK	42.24	C	82	I	83	8	16,654	43,700	39,500
Travis AFB	CA	29.49	C	85	I	86	5	7,270	10,190	38,000
Twin Cities AFRB	MN	33.62	I	86	C	91	0	1,531	2,900	2,500
Williams AFB	AZ	37.93	C	84	I	86	5	4,078	11,600	35,834
Wright-Patterson AFB	OH	57.85	C	82	I	86	5	56,110	68,896	395,982
	Total							429,254	679,222	3,830,132
	Avg	40.02					4.09	13,414	24,258	136,790

NOTES: * #1 is the Wash Rack/Treatment Area
#2 is the American Lake Garden Tract
I = Initiated
C = Completed

Appendix B

Nominal Variables

Appendix B defines the decision support model variables and lists the nominal values used to validate the model. In addition, the values and names where entered in an EXCEL™ spreadsheet and linked to the model created in DPL™.

Table B-1

Objective Function Variables

Value	Name	Definition
20000	max cost	Maximum possible project cost
110	max duration	Maximum possible project duration
0.33	alpha	Degree of preference of miminizing cost versus minimizing duration

Table B-2

Nominal Cost and Duration Variables

Value ($)/ (months)	**Name**	**Definition**
3500	FCcost	Cost of implementing the Fully Characterize option
24	FCdur	Duration of Implementing the Fully Characterize option
2000	CMLcost	Cost of implmenting the Characterize Most Likely option
12	CMLdur	Duration of implmenting the Characterize Most Likely option
2500	ALLcost	Cost of implementing the Investigate All option
24	ALLdur	Duration of implementing the Investigate All option
500	PRcost	Cost of implementing the Presumptive Remedy option
7	PRdur	Duration of implementing the Presumptive Remedy option
2250	RAno cost	Additional cost if Remedy is not Acceptable
22	RAno dur	Additional duration if Remedy is not Acceptable
5000	MCGyes cost	Cost if initial remedy Meets Cleanup Goals
36	MCGyes dur	Duration it initial Remedy Meets Cleanup Goals
4000	MCGno cost	Additional cost if initial remedy does not Meets Cleanup Goals
24	MCGno dur	Additional duration if initial remedy does not Meets Cleanup Goals
1000	DIyes cost	Cost if Deviations are Implemented
6	DIyes dur	Duration if Deviations are Implemented

Table B-3

Nominal Likelihood Variables

%	Name	Definition
0.65	P(SSR)	Likelihood Site Similarity Report predicts true state
0.75	P(TSS)	Likelihood site is Truly Similar
0.95	P(RA g/all)	Likelihood Remedy is Acceptable given Investigate All
0.75	P(RA g/pr)	Likelihood Remedy is Acceptable given Presumptive Remedy
0.95	P(SCM g/FC)	Likelihood Site Model predicts true state given Fully Characterize
0.6	P(SCM g/CML	Likelihood Site Model predicts true state given Characterize Most Likely
0.7	P(DI)	Likelihood Deviations are Implemented if required
0.95	P(MCG g/DIyes)	Likelihood Meets Goals given Deviations are Implemented
0.95	P(MCG g/DIno&yes)	Likelihood Meets Goals given Deviations are not Implemented and Site Model predicts true state
0.01	P(MCG g/DIno&no)	Likelihood Meets Goals given Deviations are not Implemented and Site Model does not predicts true state
0.5	P(TSP)	Likelihood True Site Parameters are Set A

Appendix C

Decision Support Model as Programmed in DPL™

The decision support model as described in chapter 3 was programmed in DPL™. DPL™'s programming requirements are unique. There are two methods of programming within DPL™, text and draw. The decision support model was programmed using the draw option. This appendix provides the programming drawings used to program the decision support model. The DPL™ model was linked to an EXCEL™ spreadsheet to import the values of the primary decision support model variables, Appendix B. Figures C-1 and C-2 are the main structure of the problem. Figure C-1 is the influence diagram portion of the program that defines each event and the relationships of these events. Figure C-1 also defines the primary decision model linked to the EXCEL™ spreadsheet and the internal variables. Figure C-2 is the decision tree portion that defines the sequence of events and the get/pay expressions used in the objective function to determine the expected value. Table C-1 lists and defines the internal variables used to capture intermediate cost and duration values. Figures C-3 through C-20 defines the values and likelihoods for each outcome of an event.

Table C-1

Internal DPL™ Program Variables

Name	Definition
fscost	Estimated costs of the chosen FS Strategy
fsdur	Estimated duration of the chosen FS Strategy
racost	Estimated costs of the Remedy Acceptable outcomes given the outcomes of FS Strategy and True Site Similarity
radur	Estimated duration of the Remedy Acceptable outcomes given the outcomes of FS Strategy and True Site Similarity
devcost	Estimated costs of the Deviations Implemented outcomes given the outcomes of Site Characterization Model and True Site Parameters
devdur	Estimated duration of the Deviations Implemented outcomes given the outcomes of Site Characterization Model and True Site Parameters
meetscost	Estimated costs of the Meets Cleanup Goals outcomes given the outcomes of Deviation Implemented, Site Characterization Model, and True Site Parameters
meetsdur	Estimated duration of the Meets Cleanup Goals outcomes given the outcomes of Deviation Implemented, Site Characterization Model, and True Site Parameters

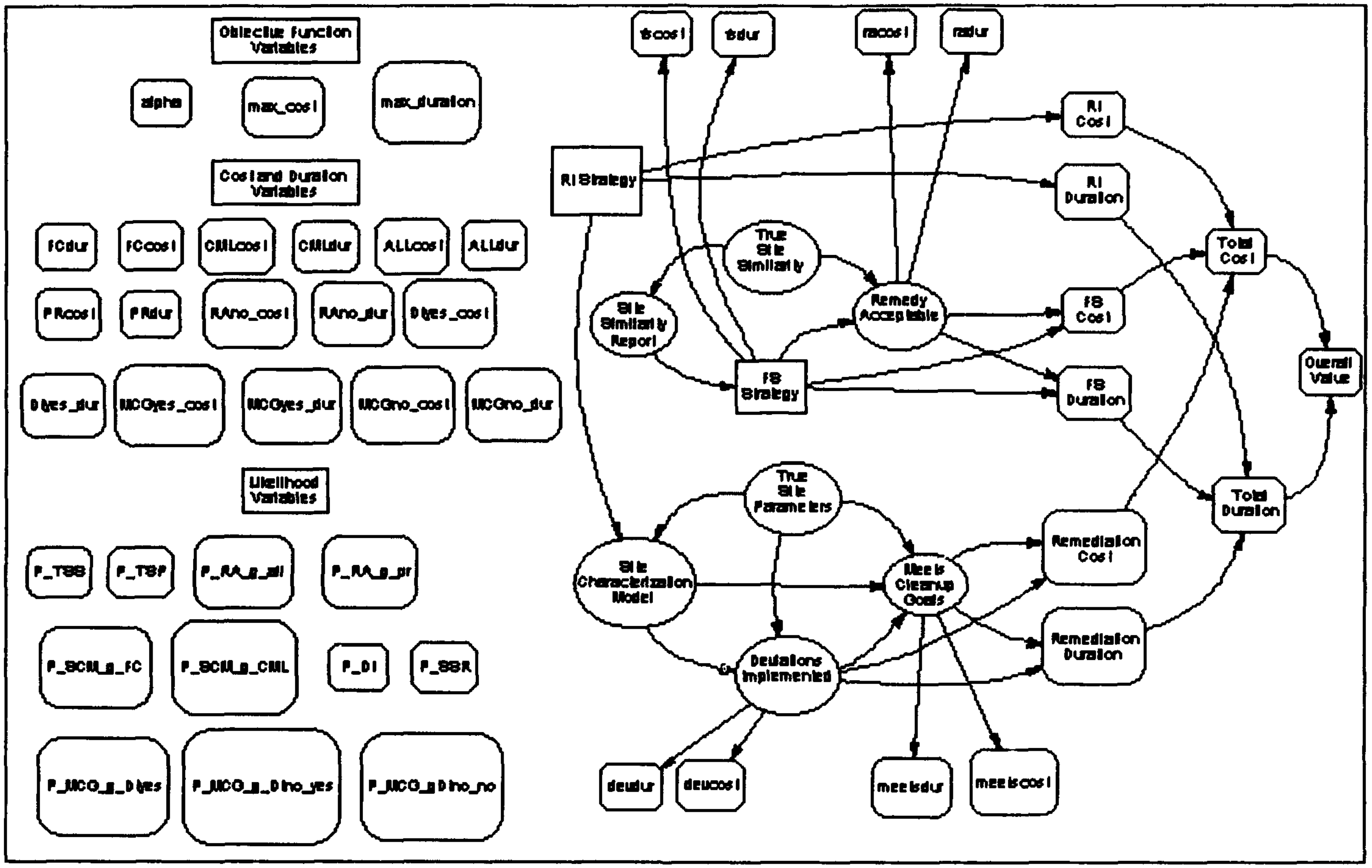

Figure C-1. Influence Diagram as Defined in DPL™.

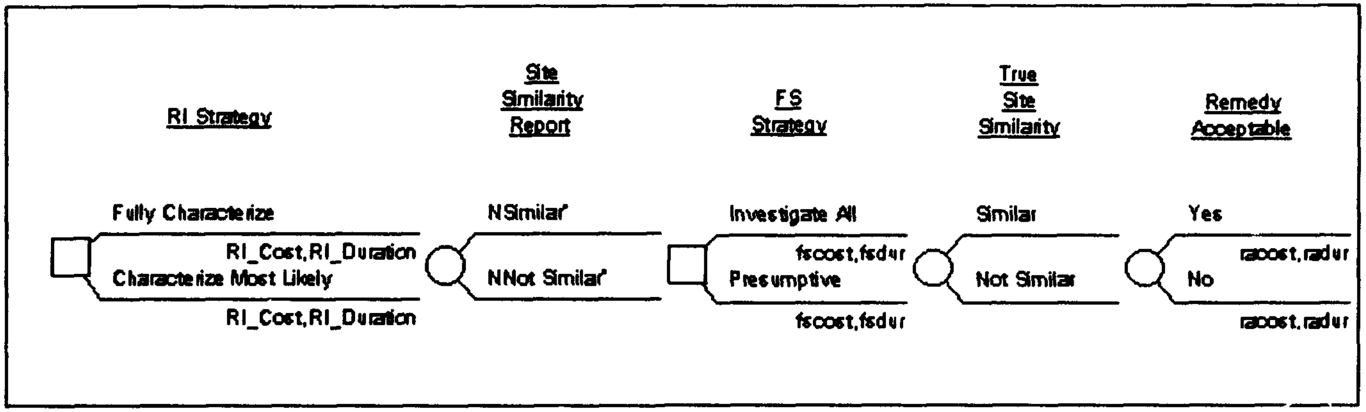

Figure C-2. First Part of Decision Tree as Defined in DPL™.

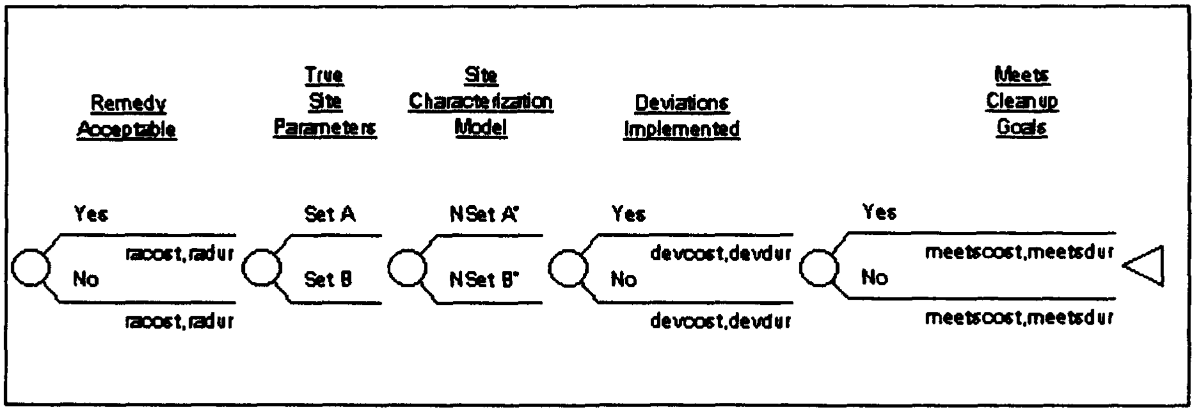

Figure C-3. Second Part of Decision Tree as Defined in DPL™.

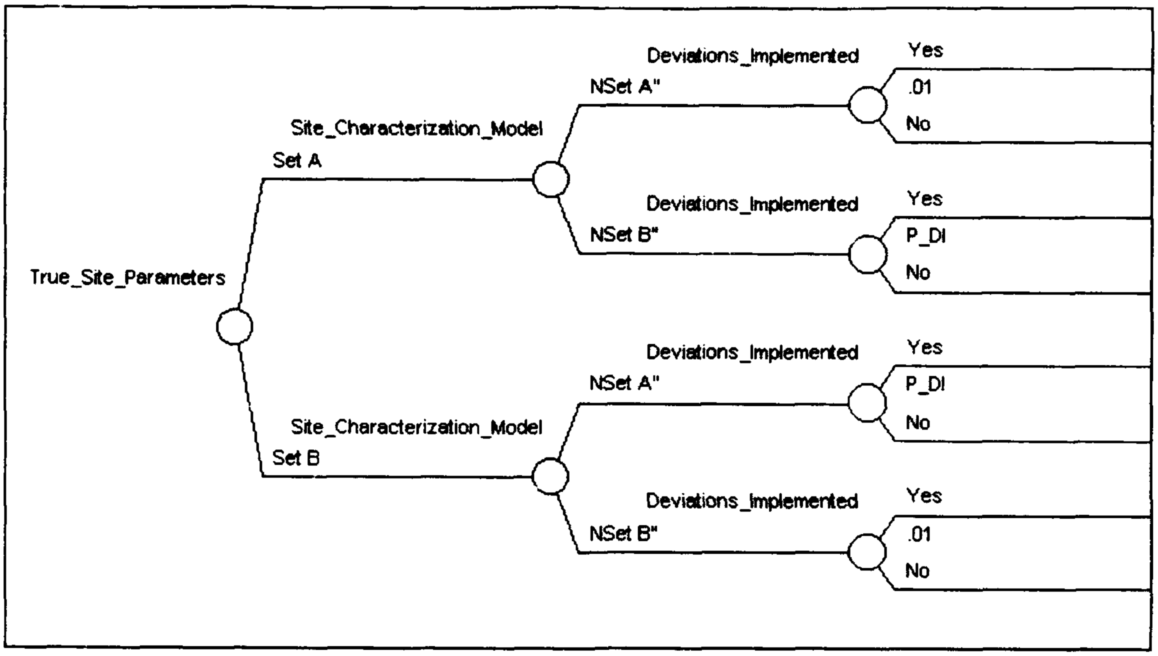

Figure C-4. Probabilities of Outcomes for the Deviations Implemented Node.

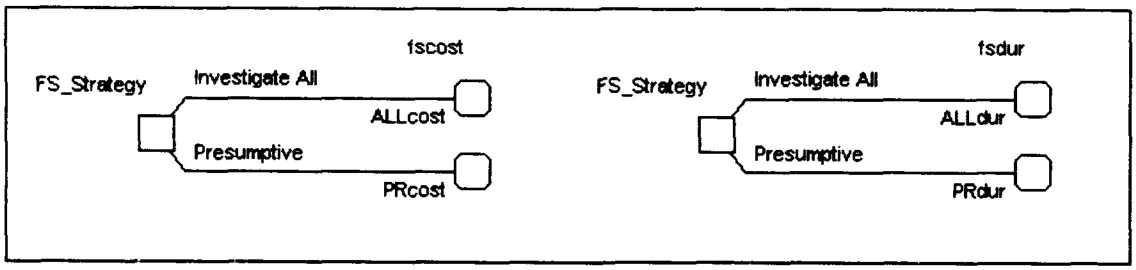

Figure C-5. Values of Outcomes for the fscost and fsdur Nodes.

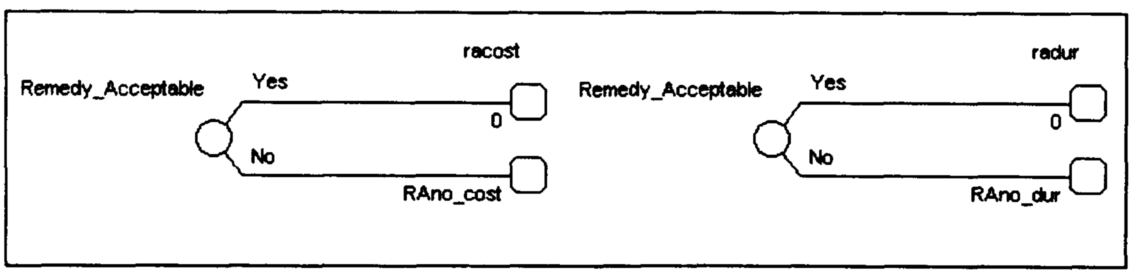

Figure C-6. Values of Outcomes for the racost and radur Nodes.

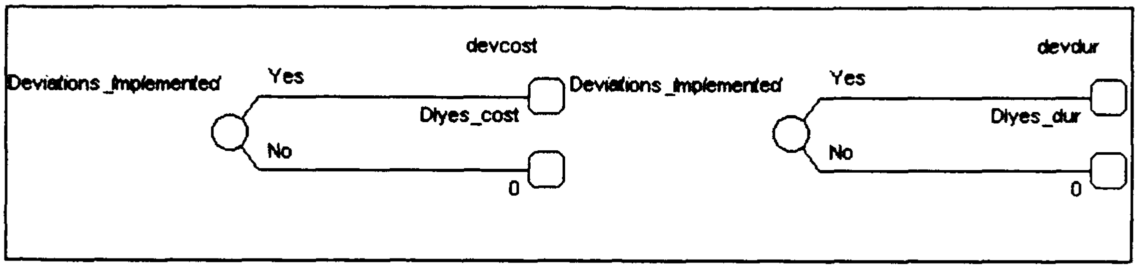

Figure C-7. Values of Outcomes for the devcost and devdur Nodes.

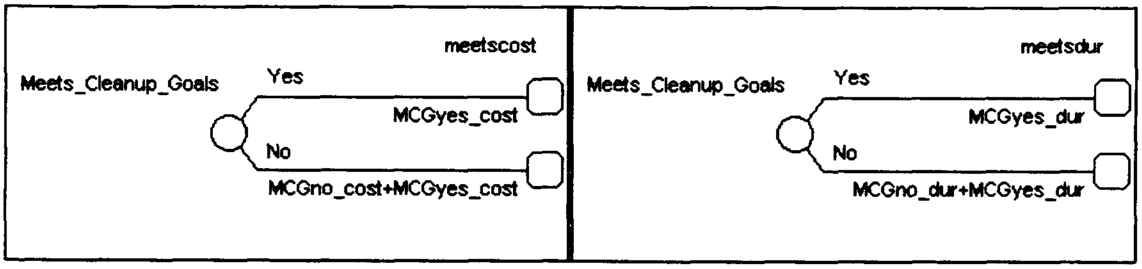

Figure C-8. Values of Outcomes for the meetscost and meetsdur Nodes.

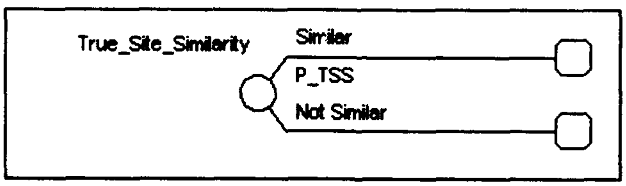

Figure C-9. Probabilities of Outcomes for the True Site Similarity Node.

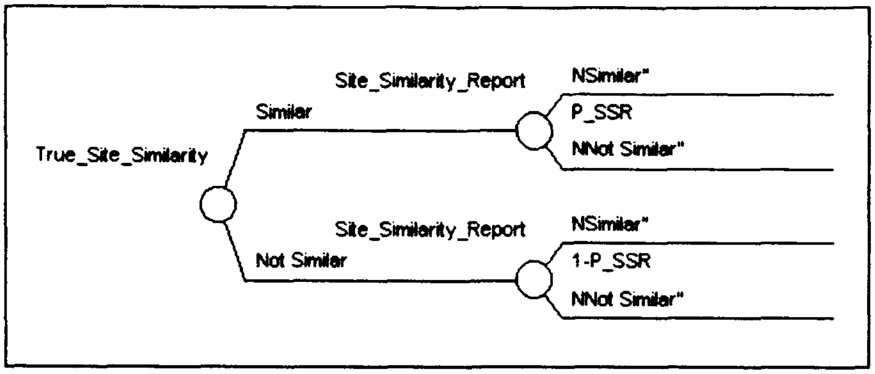

Figure C-10. Probabilities of Outcomes Site Similarity Report Node.

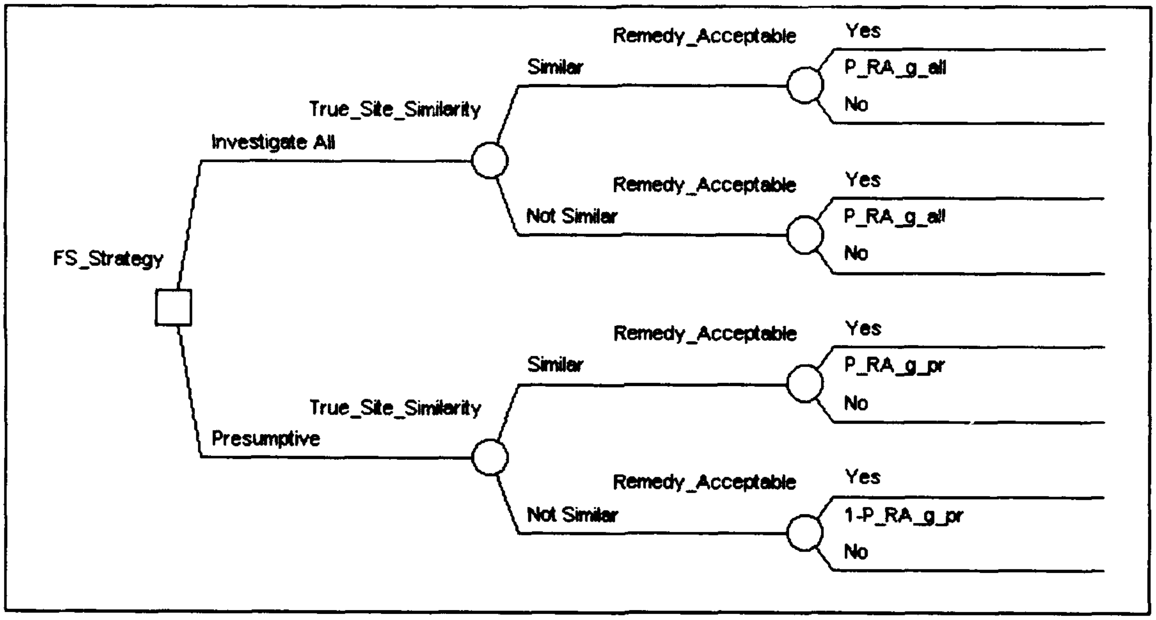

Figure C-11. Probabilities of Outcomes for the Remedy Acceptable Node.

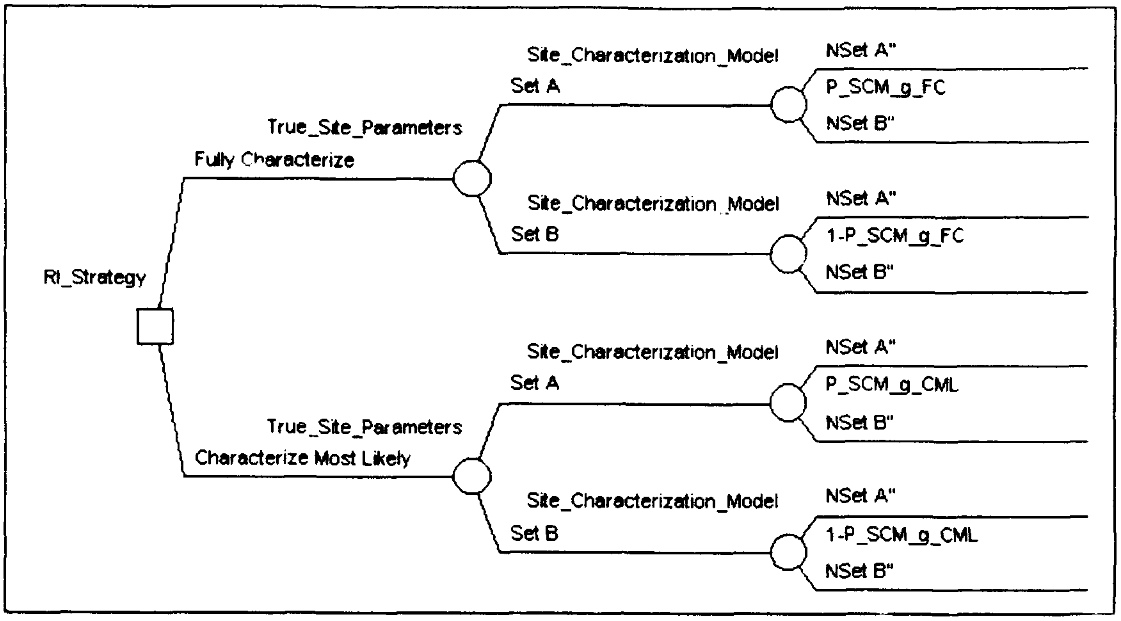

Figure C-12. Probabilities of Outcomes for the Site Characterization Model Node.

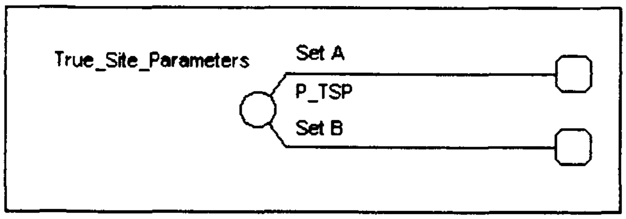

Figure C-13. Probabilities of Outcomes for the True Site Parameters Node.

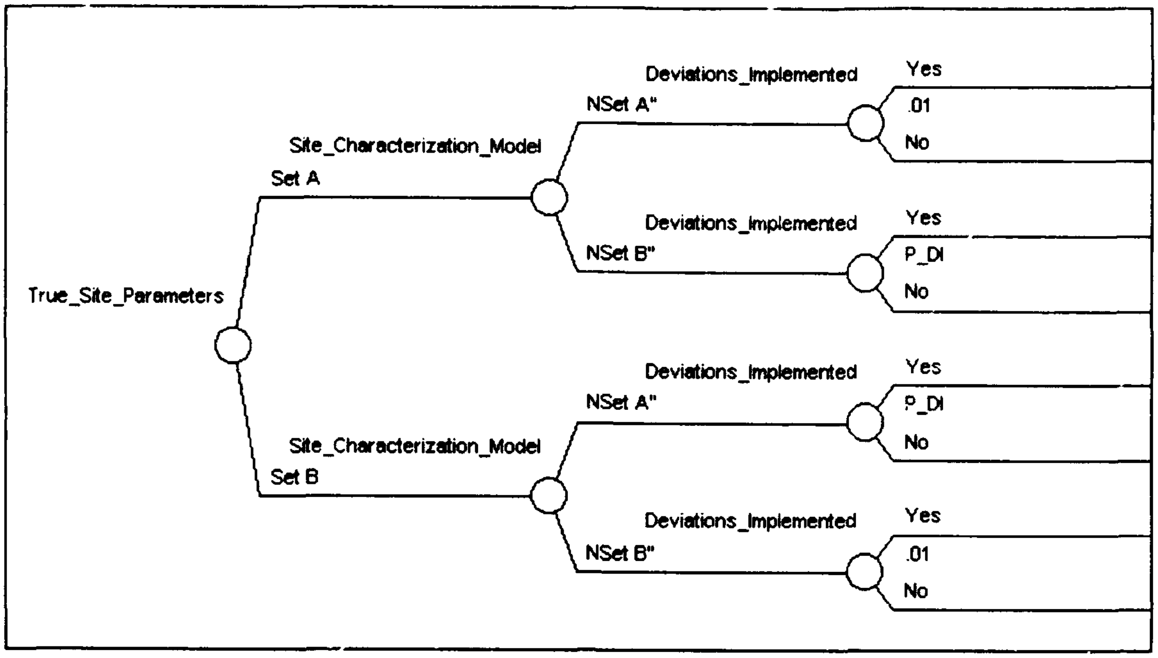

Figure C-14. Probabilities of Outcomes for the Deviations Implemented Node.

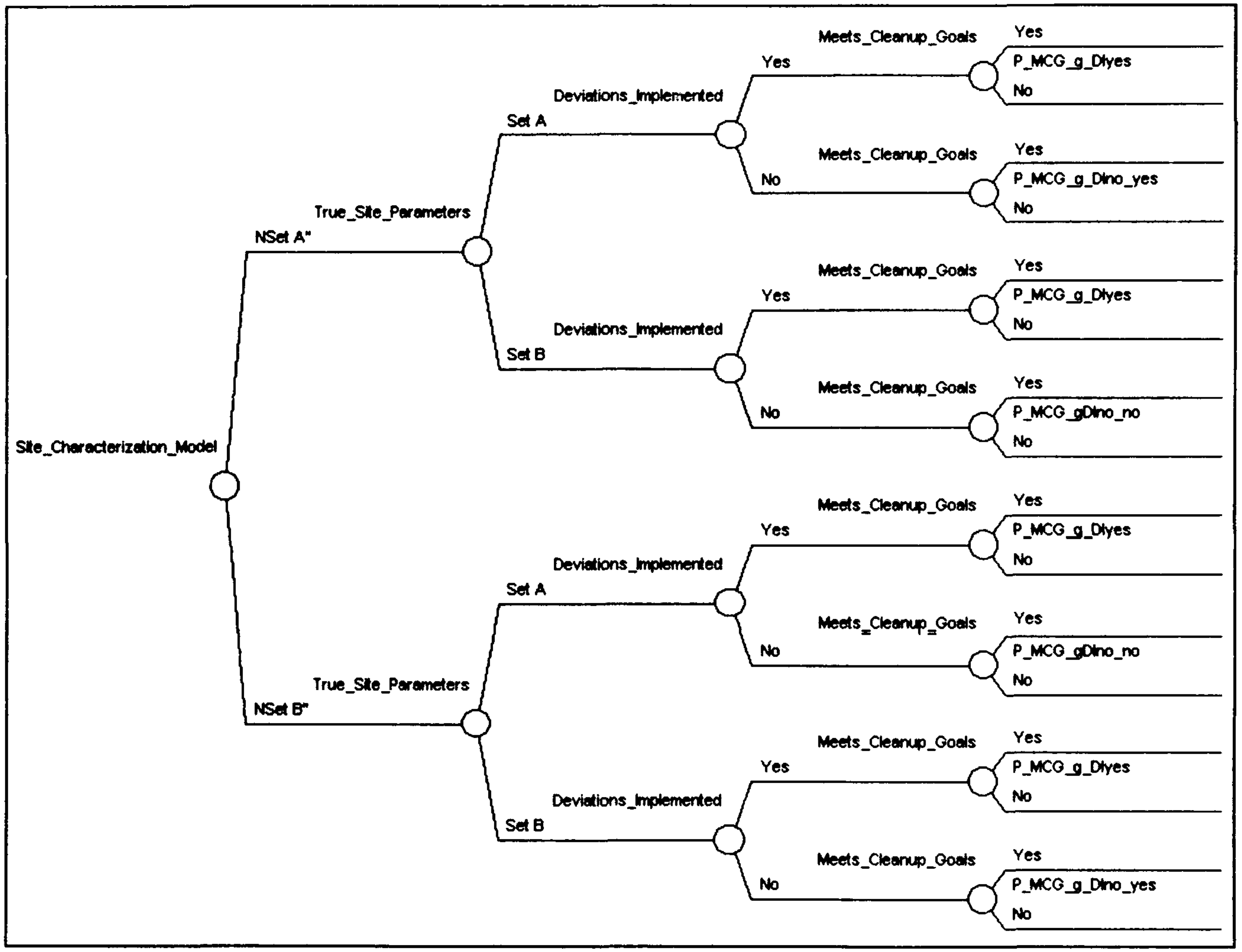

Figure C-15. Probabilities of Outcomes for the Meets Cleanup Goals node.

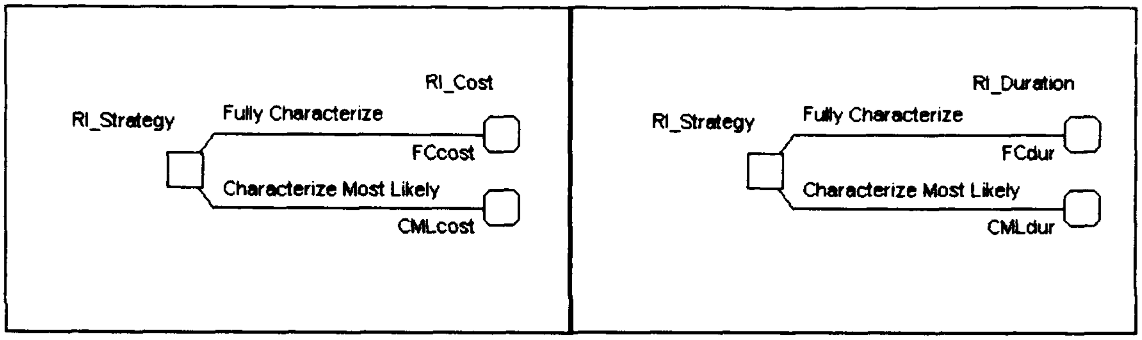

Figure C-16. Values of Outcomes for the RI cost and RI Duration Nodes.

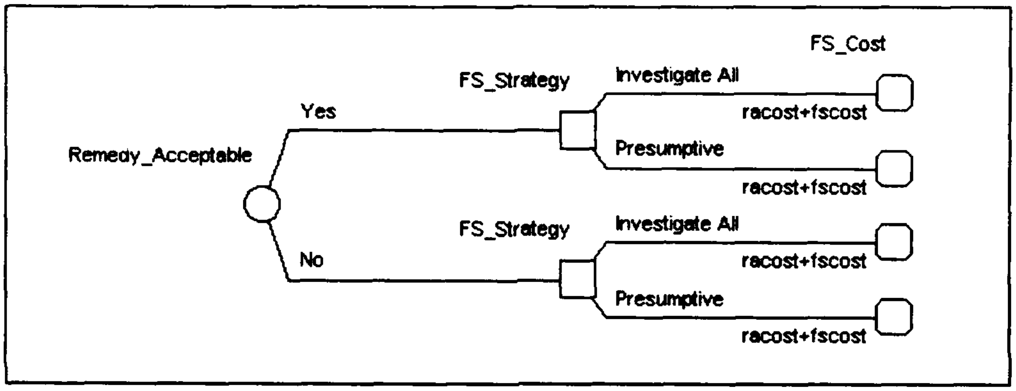

Figure C-17. Values of Outcomes for the FS Cost Node.

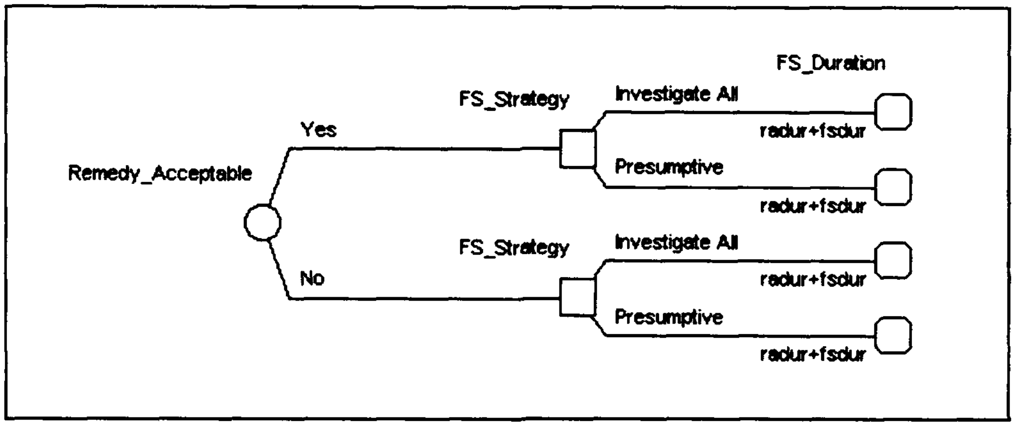

Figure C-18. Values of Outcomes for the FS Duration Node.

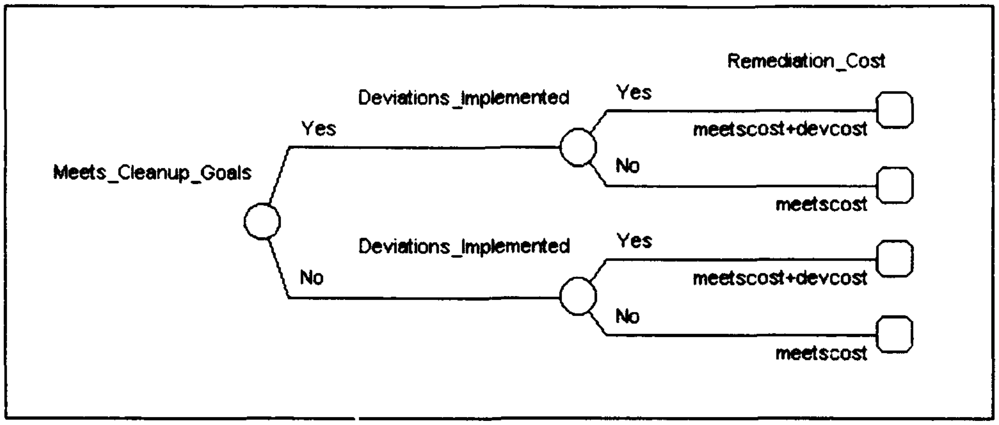

Figure C-19. Values of Outcomes for the Remediation Cost Node.

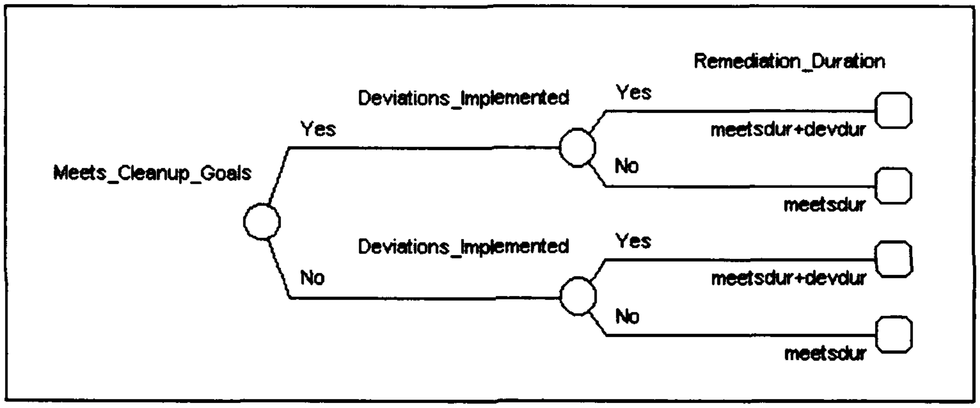

Figure C-20. Values of Outcomes for the Remediation Duration Node.

Objective Function

$$((\alpha)*(((-1/\text{max cost})*(\$1))+1))+((1-\alpha)*(((-1/\text{max duration})*(\$2))+1))$$

Where $1 = Total Cost

$2 = Total Duration

Bibliography

Brill, Angela K., Kenneth E. Darnell, and A. J. Kuhaida Jr. "New RI Approach for HTRW Sites," The Military Engineer, 86: 51-52 (March-April 1994).

Brown, Stuart M., David R. Lincoln, and William A. Wallace. "Application of Observational Method to Hazaerdous Waste Engineering," Journal of Management in Engineering, 6: 479-500 (October 1990).

Checile, Richard A. and Susan Carlisle. Environmental Decision Making A Multidisciplinary Perspective. York: Van Nostrand Reinhold, 1991.

Clemens, Robert T. Making Hard Decisions: an Introduction to Decision Analysis. Boston: PWS-Kent Publishing, 1991.

Cromwell, Vern, Mickey Hartnett, Judith Wright, and John April. "Using the Observational Approach for Streamlined Environmental Remediation," Address to Air Force Installation Restoration Management Meeting, Denver CO February 9, 1994.

Dean, A. and M. Barvenik. "Use of the Observational Method in the Remedial Investiagtion and Clean-up of Contaminated Land," Geotechnoque, 41: 33-36 (March 1, 1992).

Department of Defense. Defense Environmental Restoration Progam Annual Report to Congress for Fiscal Year 1991. Washington: GPO, February 1992.

Department of the Air Force. USAF Installation Restoration Program Remedial Project Manager's Handbook. Washington: HQ USAF, January 1992.

DPL™. Advanced student version 3.1, IBM, 1.4M, disk. Computer software. ADA Decision Systems, Menlo Park CA, 1992.

Duplancic, Neno and Gregory Buckle. "Hazardous Waste: Quicker Cleanup," Forum For Applied Research and Public Policy, 8: 50-56 (Spring 1993).

Duplancic, N. and G. Buckle. "Hazardous Data Explosion," Civil Engineering, 59: 68-70 (December 1989).

Edwards, Scott. HQ USAF/CEV Washington DC. Telephone Interview February 18, 1994.

Einstein, Herbert H. "Observation Quantification and Judgement. Terzaghi and Engineering Geology," Journal of Geotechnical Engineering, 117: 1772-1778 (November 1991).

Elliot, E. Donald. "Superfund: EPA Success, National Debacle?," Natural Resources & Environment, 6: 11-13, 48-50 (Winter 1992).

Ember, Lois. "Industry Coalitition Offers Fixes for Tropubled Superfund," Chemical and Engineering News, 72: 30-31 (19 April 1993).

Ember, Lois. "Industry Coalition Slows Superfund," Chemical & Engineering News, 71: 19 (2 August 1993).

"Environmental Restoration Effort Takes on Momentum," National Defense, 78: 16-17 (occtober 1993).

Gianti, Sam. Class handout, ENVR 560, Environmental Monitoring. School of Engineering, Air Force Institute of Technology, Wright-Patterson AFB OH Winter Quarter 1994.

Gianti, Sam. Class lecture, ENVR 560, Environmental Monitoring. School of Engineering, Air Force Institute of Technology, Wright-Patterson AFB OH Winter Quarter 1994.

House Committee on Armed Services. Environmental Restoration Panel. Hearings To Review Issues Related to the Clean Up of DoD National Priority List Sites and Compliance With the Solid Waste disposal Act. Hearing, 100th Congress, 2nd Session, 1988. Washington GPO, 1988.

Lee, Robert T. Environmental Law Handbook (Twelfth Edition). Rockville, Md: Government Industitutes, 1993.

Peck, R. B. "Advantages and Limitations of the Observational Method in Applied Soil Mechanics," Geotechnique, 19: 171-187 (June 1969).

Rudolph, Thomas E. AFMC CERCLA/IRP Legal Review Guide 1993. Wright-Patterson AFB: HQ AFMCLC/JAV, 1993.

Russell, Milton and others. Hazardous Waste Remediation: The Task Ahead. Knoxville, TN: Univiersity of Tennessee, December 1991.

USEPA, Office of Solid Waste and Emergency Response. Superfund Progress, Summer 1992. Report series 9200.1-12-2. Washington: GPO, 1992.

USEPA, Office of Solid Waste and Emergency Response. Superfund Progress - Aficionado's Version. Report Series 9200.1-12B. Washington: GPO, August 1992.

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September 1994 Master's Thesis

DECISION SUPPORT MODEL TO COMPARE HAZARDOUS WASTE SITE REMEDIATION PROCESS ALTERNATIVES

Christopher E. Findall, Captain, USAF

Air Force Institute of Technology, WPAFB OH. 45433-6583

AFIT/GEE/ENV/94S-09

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This research focuses on the development of a decision support model to identify the preferred methods of site characterization and treatment technology identification using the principles of decision analysis theory. The model provides an effective decision making tool to evaluate and compare the feasibility of using alternative methods of completing the RI/FS process. Given a specific site remediation project, the users of this model can enter site-specific cost, duration and likelihood values to determine the expected value for various alternative processes. This thesis postulates that the alternative having the highest expected value is considered the "preferred' alternative. In calculating the expected value of an alternative, the cost and duration for each alternative and outcome of uncertain events are evaluated. This research also includes a representative case study to illustrate the use of the decision support model.

Hazardous Waste, Decision Making, Observational Method, Presumptive Remedy

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